CMB Non-Gaussianity from Recombination and Hints for Dark Matter Off the Beaten Track

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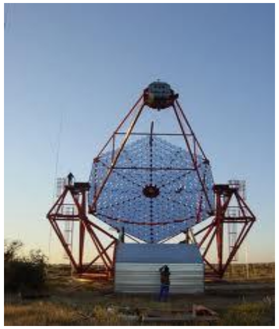
LBNL 02/14/2013

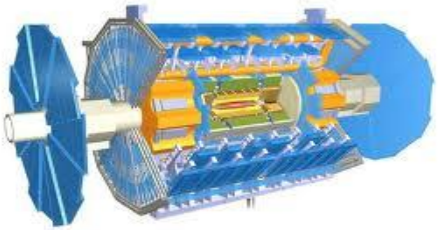
A Good Puzzle

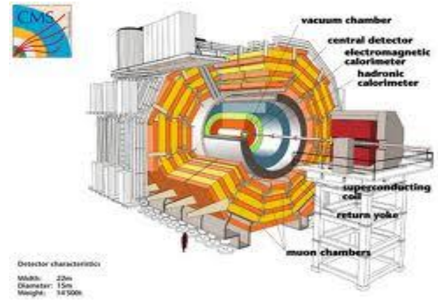
Constituents of the Universe

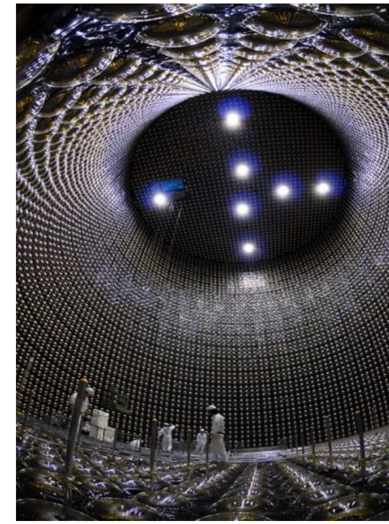
Λ?
Dark Matter?
Baryons?
Radiation

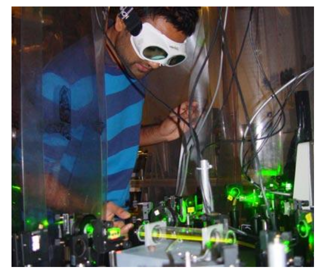
Should use everything we've got

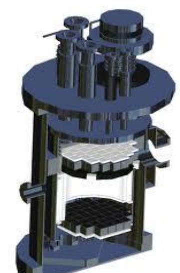


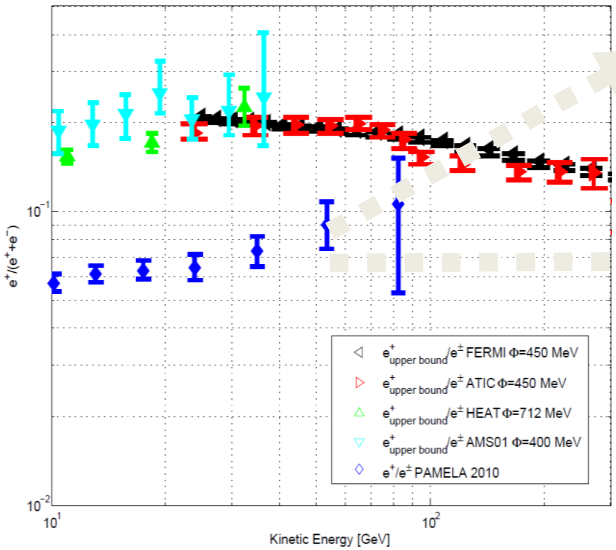


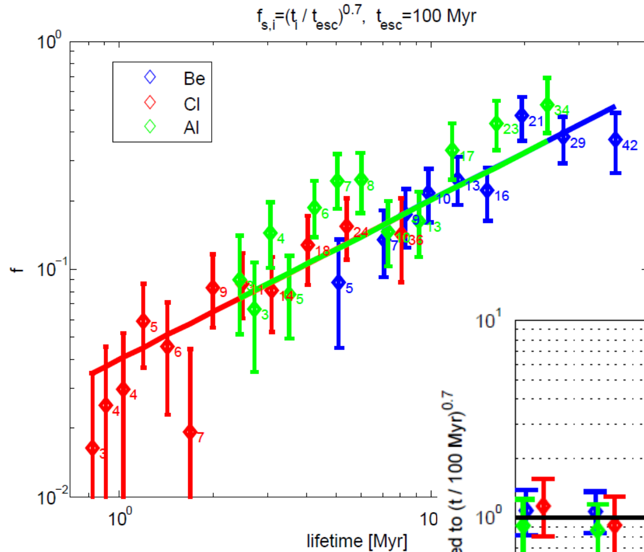


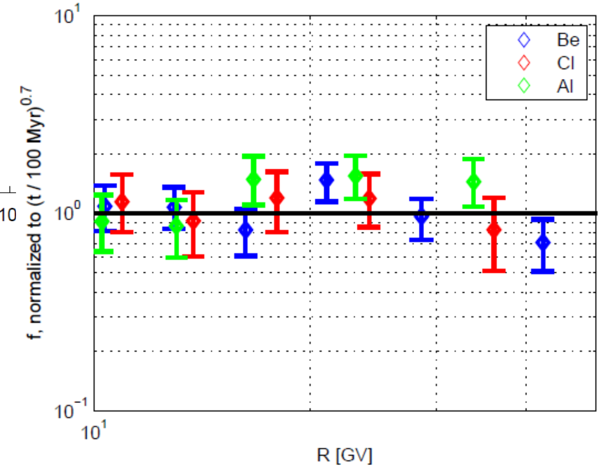












New cosmic ray data

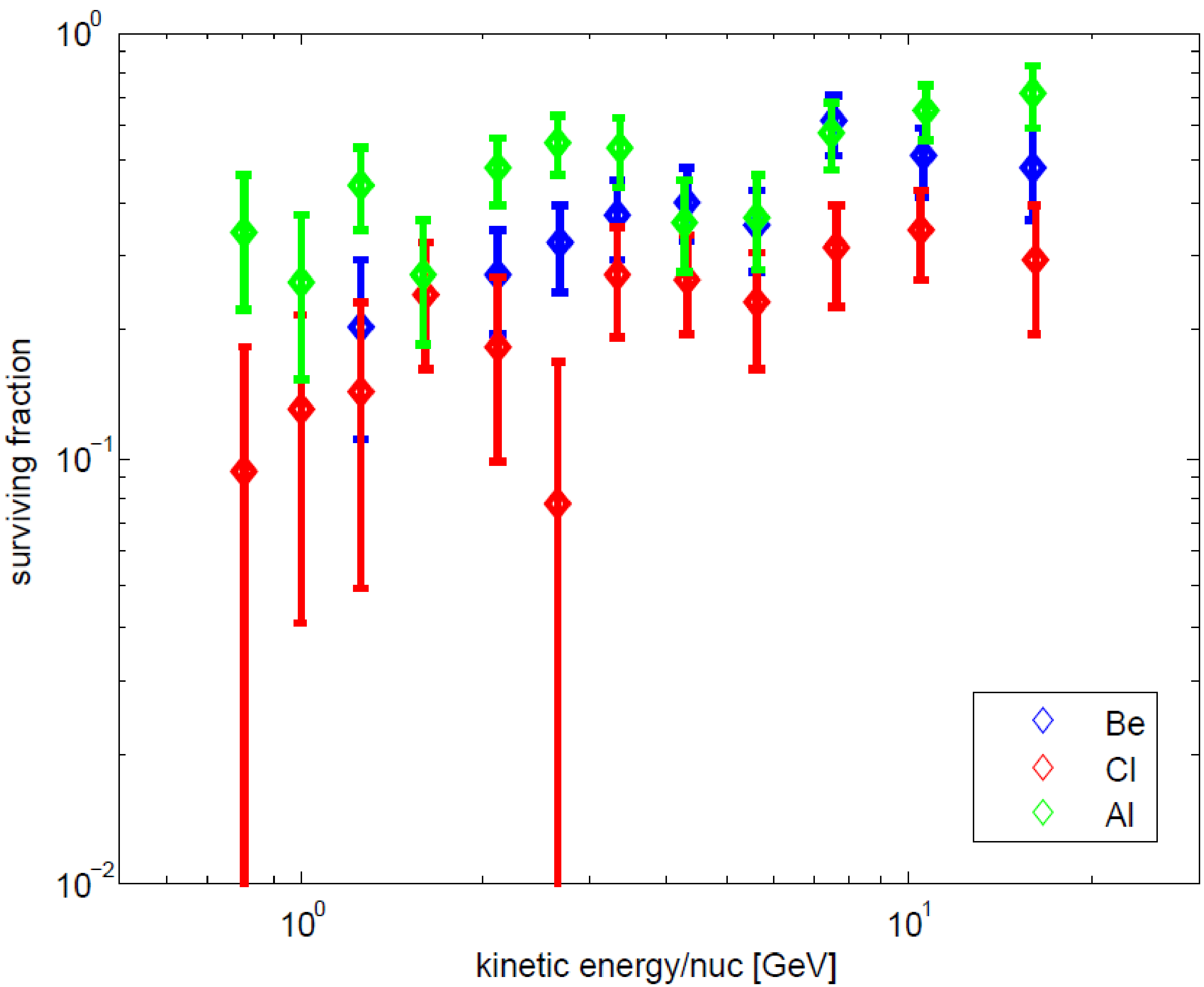
Lots of stones to turn! Lots of basic facts to learn about our Galaxy

Will we see clues of dark matter?

Katz, KB, Waxman, MNRS 405, 1458–1472 (2010); KB, JCAP11(2011)037

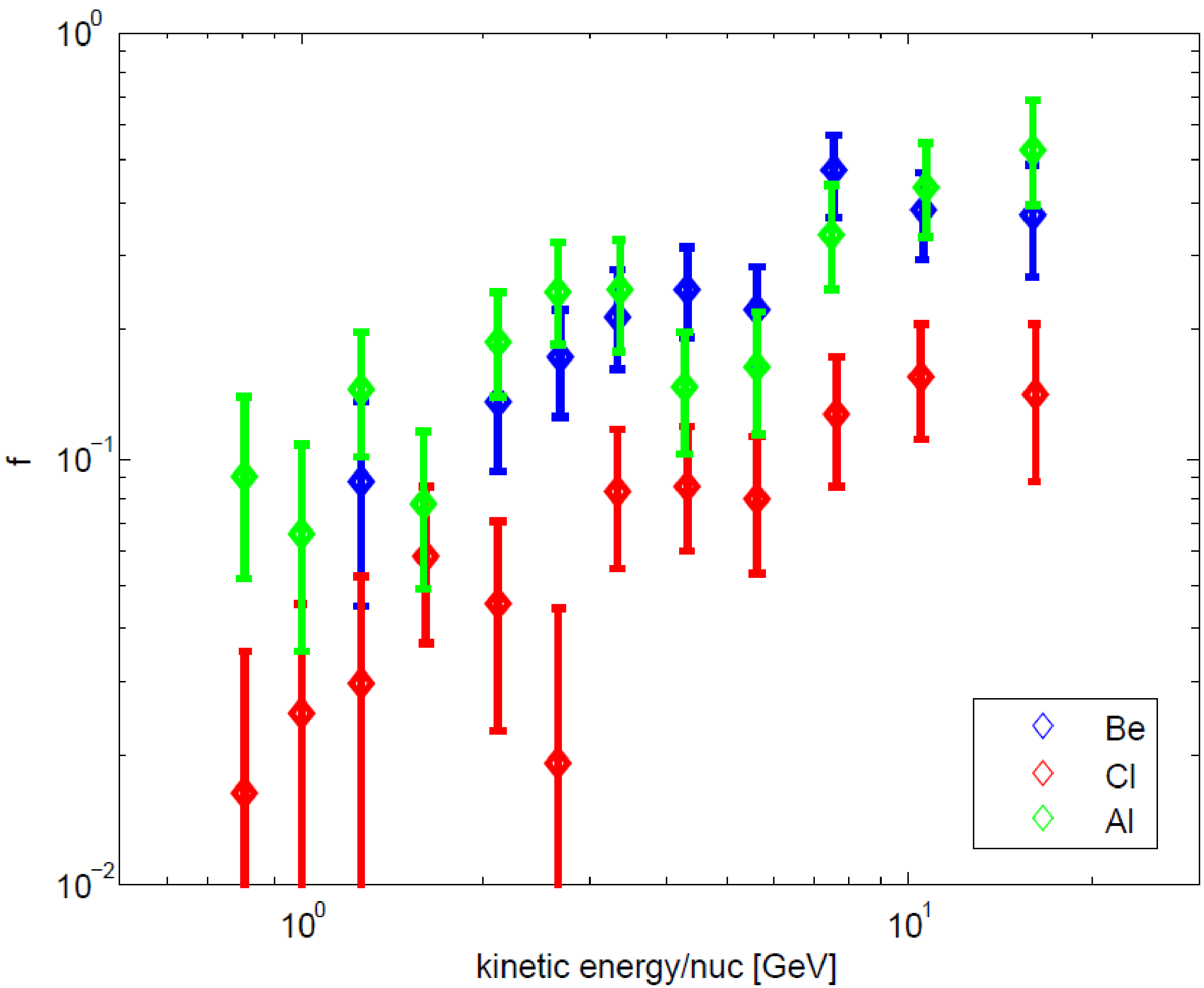
Radioactive nuclei: data

Surviving fraction vs. energy (WS98)



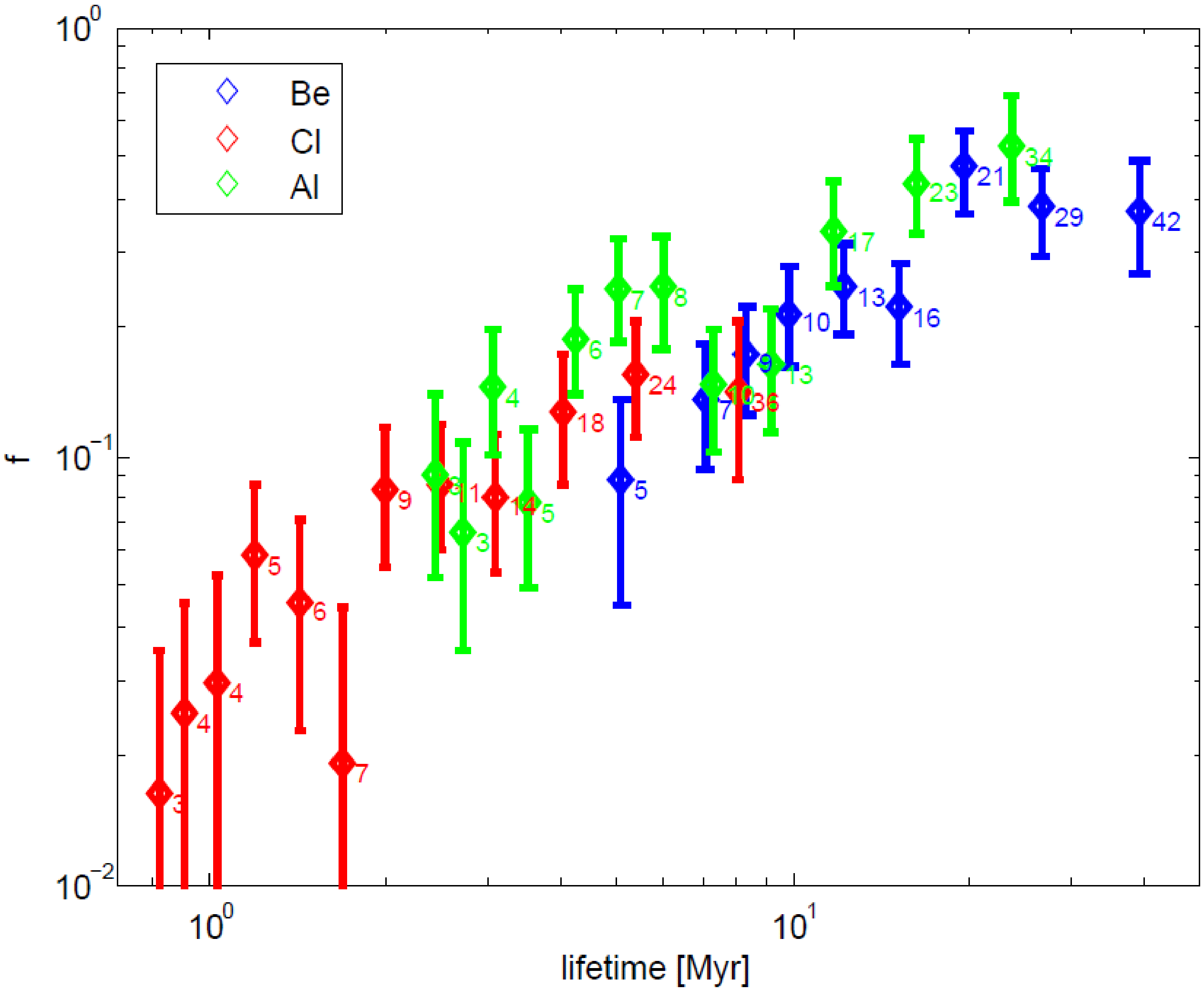
Radioactive nuclei: data

Suppression factor vs. energy



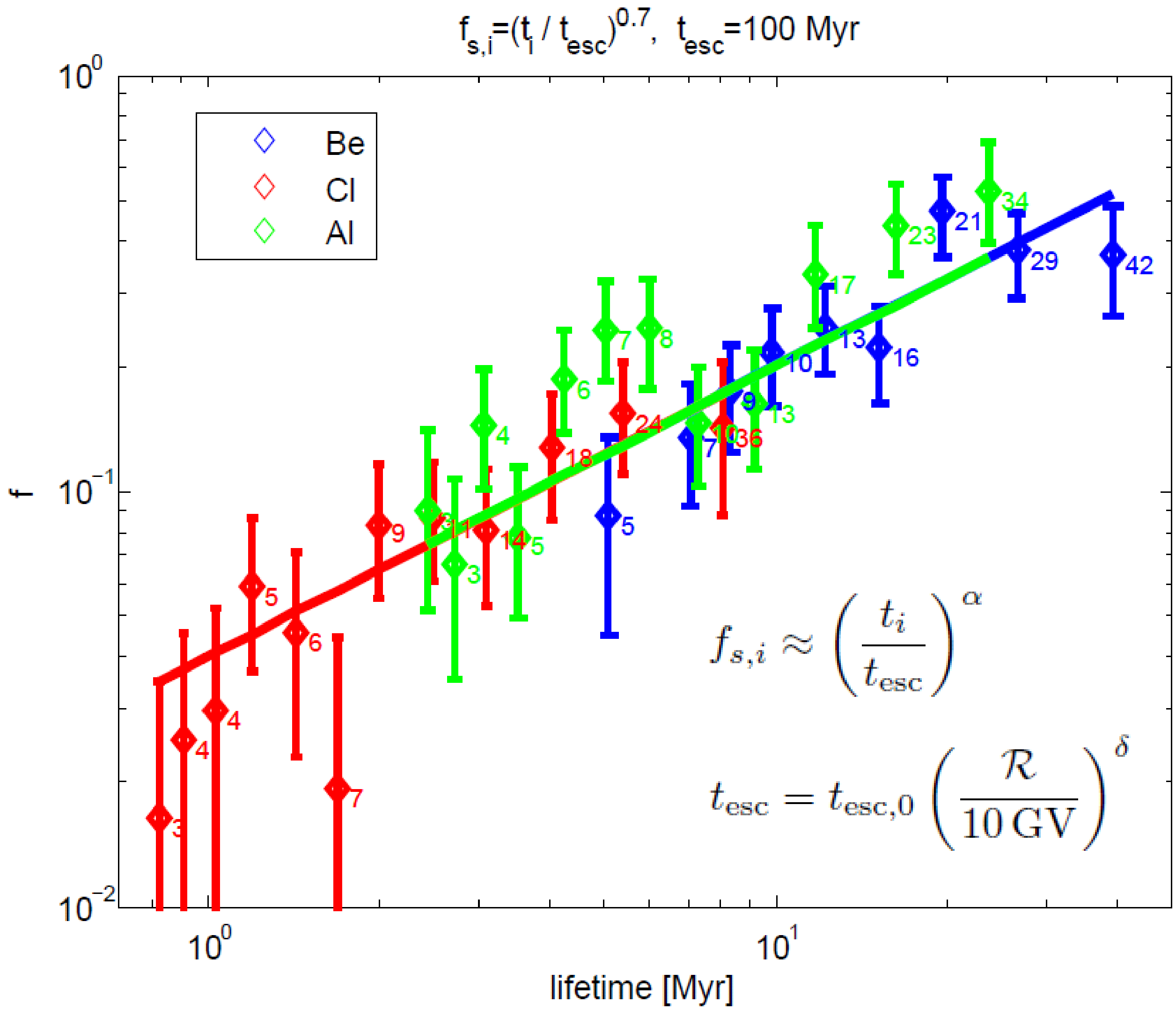
Radioactive nuclei: data

Suppression factor vs. lifetime



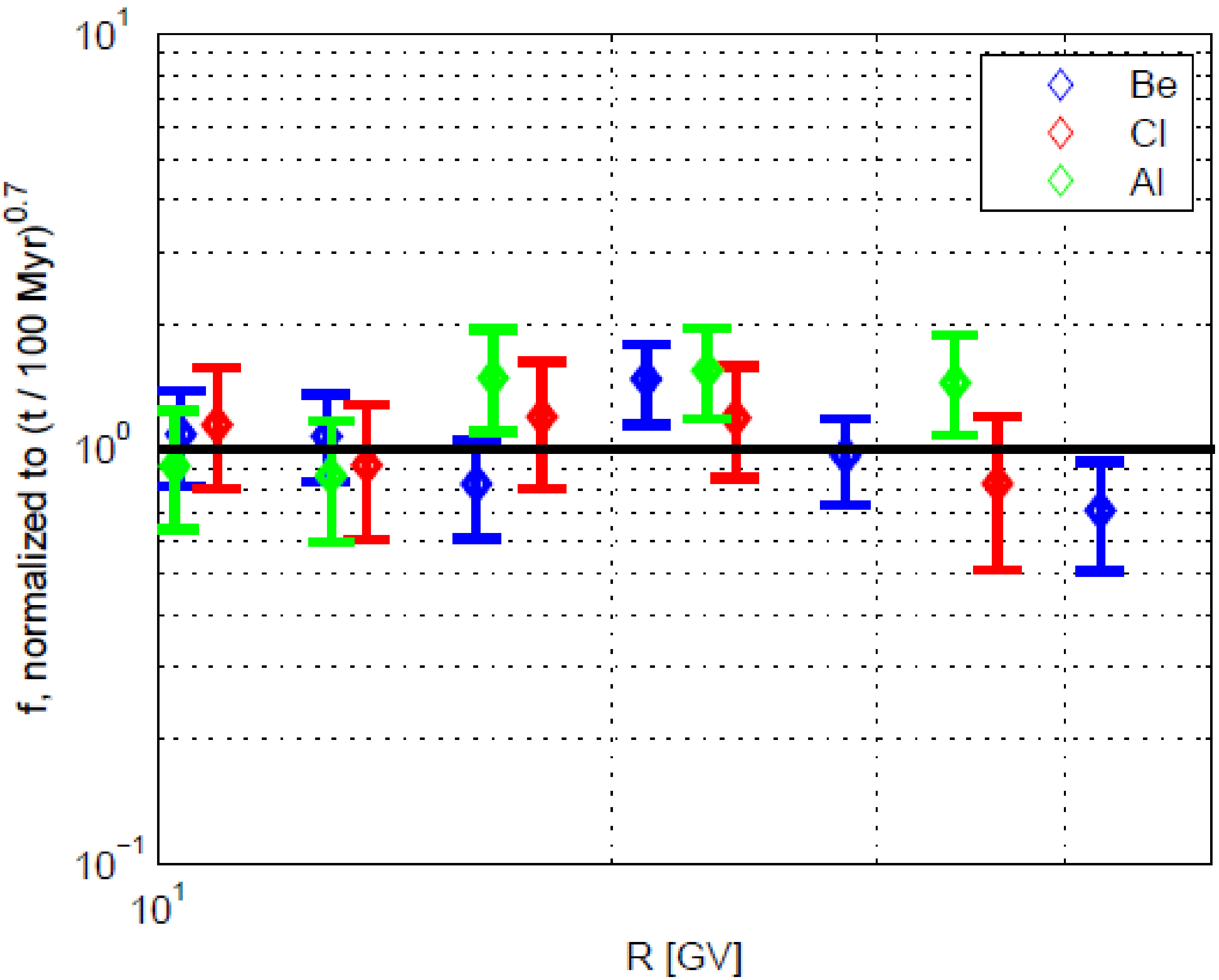
Radioactive nuclei: data

Consistent with constant residence time **KB, JCAP11(2011)037**

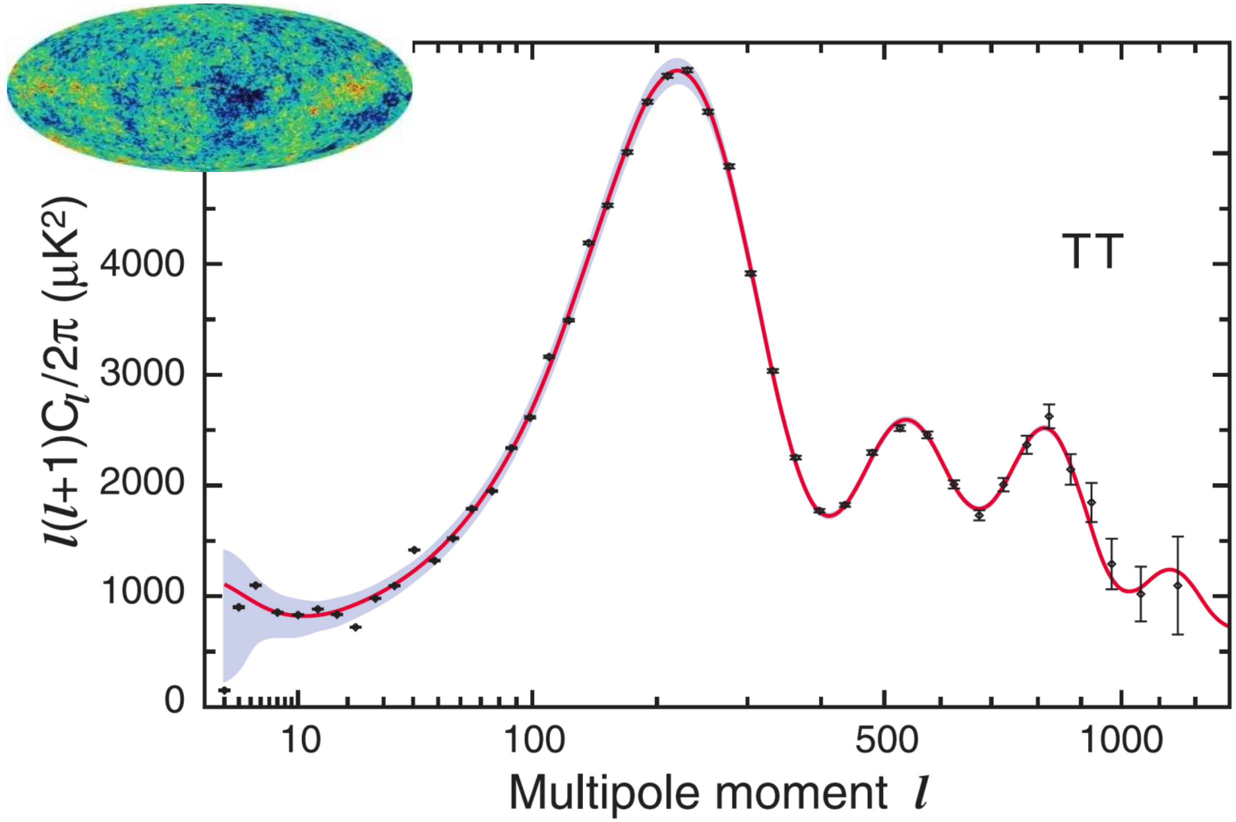


Radioactive nuclei: data

Residual rigidity dependence



CMB in intricate detail

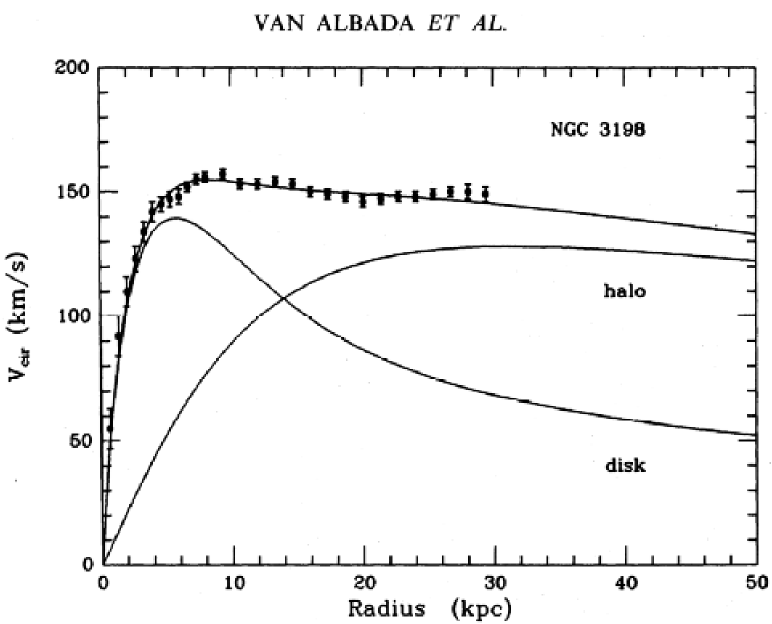


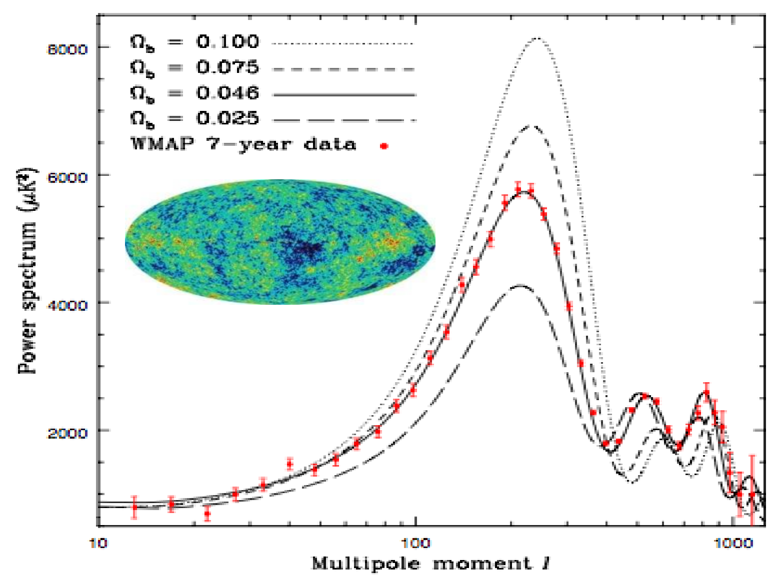
SM predictions beat cosmic variance. Will it hold? Will we learn about inflation?

Dark matter

Overwhelming evidence for dark matter. All gravitational
Galaxy scale
Cluster scale
Cosmic Microwave Background

As far as current observations go, DM can equally well be in axions as in black holes the size of the Earth. May be completely sterile…





Theoretical motivation for WIMPs and their like

1. **Naturalness** -- new particles at the TeV.
Stabilization – common consequence of explaining why we have not seen it so far, using some symmetry. E.g. R-parity

2. **Thermal freeze-out**

Reminder:
Freeze-out

$$\langle \sigma v \rangle n = \frac{\langle \sigma v \rangle \rho}{m} = H = \frac{T_d^2}{M_{pl}}$$

WIMP – non-relativistic $\rho = m(mT_d)^{3/2} e^{-m/T_d}$ ➔ $T_d = m/10$

$$\rho(T_d) = (T_d/T_0)^3 \rho_0 \quad ➔ \quad \langle \sigma v \rangle = \frac{m T_d^2}{M_{pl}\rho} = \frac{T_0^3}{M_{pl}\rho_0} = 3 \times 10^{-26}\,\mathrm{cm}^3/\mathrm{s}$$

purely observable quantities

TeV particle exchange; Dark matter should be at the bottom of the spectrum

Theoretical motivation for WIMPs and their like

$\Omega_{dm} \sim 5\ \Omega_b$. Why?

Luminous matter (stars) is relic charge. In ADM, so is dark matter

3. **Asymmetric DM**

Given m/m_{proton} =O(1), explaining Y_x/Y_b =O(1) explains $\Omega_{dm}/\ \Omega_b$

- WIMPs do not do this
- ADM does: Y_x and Y_b related algebraically

In other words:

Imagine m/m_{proton} =O(1), but take $Y_b \rightarrow 10^{-20}\ Y_b$.

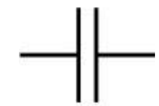
- "WIMP miracle" works as usual: $\Omega_{dm} \sim 0.2$
- ADM would not work: $\Omega_{dm} \sim 10^{-20}$

Consider: relic asymmetry set by chemical equilibrium at high scale, frozen out when DM still relativistic

Why light: first-year electronics lab

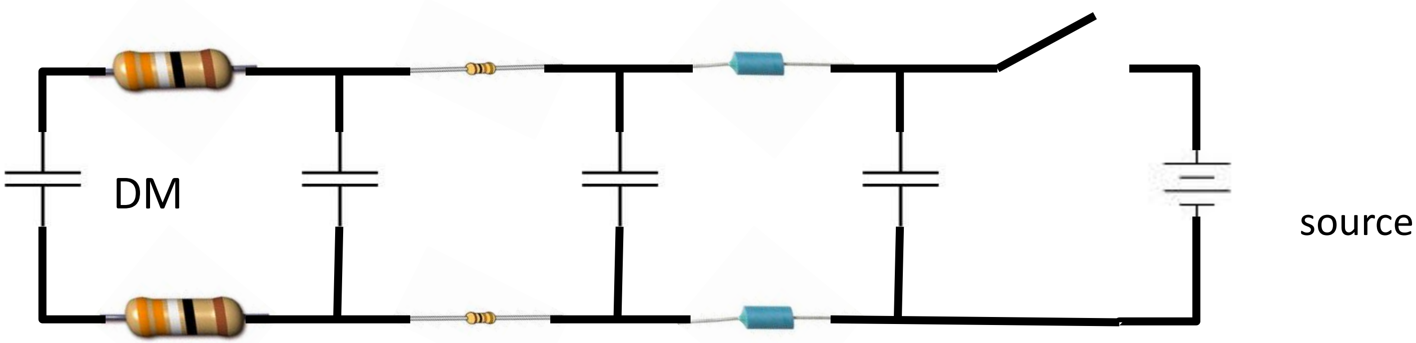
Charges = comoving particle-antiparticle asymmetries

Capacitance: **$C \sim e^{-m/T}$**



Currents flow along interaction vertices

Resistance comes about because the Universe expands: **$R \sim H/\Gamma$**



$Q_{dm}/Q = (C_{dm})/(C_{dm}+C_{SM})$ ➔ $\Omega_{dm}/\Omega_b = (m/m_{proton})(C_{dm})/(C_{dm}+C_{SM}) = 5$

$m = 5\,(1 + C_{SM}/C_{dm})\, m_{proton}$

Consider: relic asymmetry set by chemical equilibrium at high scale, frozen out when DM still relativistic

Why light: first-year electronics lab

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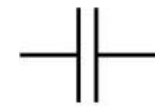

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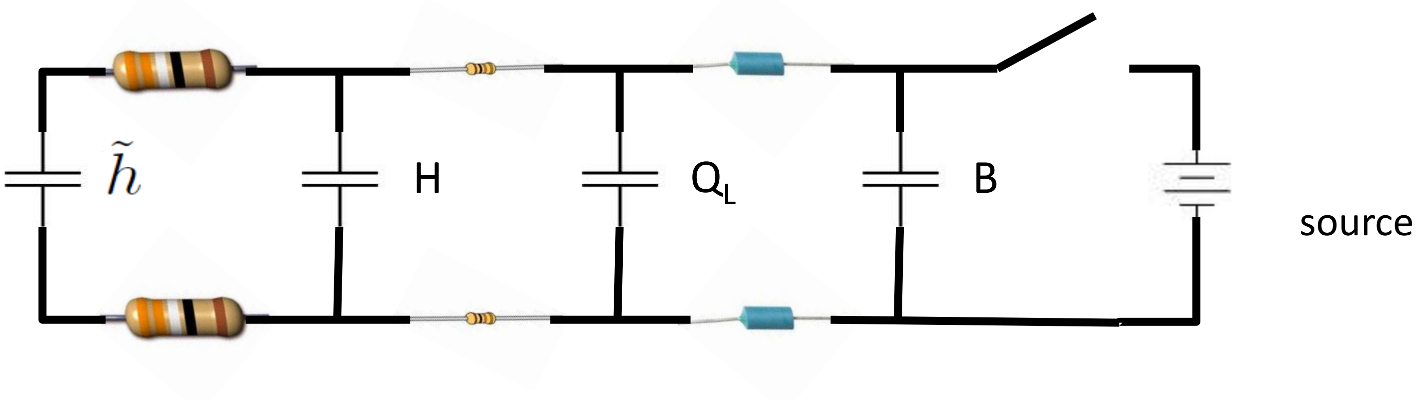


Example: relic higgsino asymmetry **KB, Efrati, Grossman, Nir, Riotto; PRL 109.051302**

At some early stage (e.g. Seesaw), Universe loaded with baryon number B (really B-L)

Transferred to chiral charge through weak sphalerons

Tranferred to Higgs charge through Yukawa

Transferred to higgsino charge through supergauge.

Looking for dark matter off the beaten track

KB, Dvorkin, Zaldarriaga

Looking for dark matter off the beaten track

Think WIMPs.

➔ **Find where dark matter *interactions* matter**

<u>Some well known avenues:</u>
TeV neutrinos from the Sun;
excess high energy cosmic ray anti-matter;
missing energy at colliders;
isolated, large nucleon recoil deep underground;
gamma-ray lines;
…

Conceivably find DM in one of those soon!

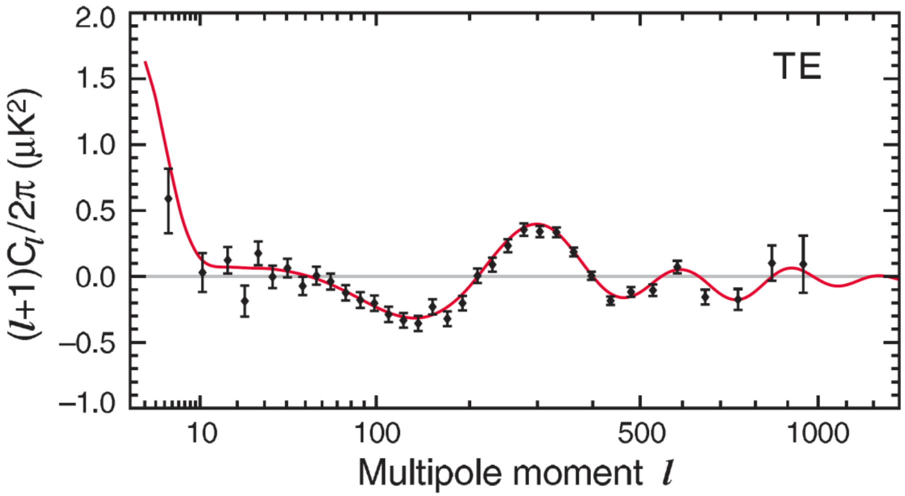
Important to look for new processes

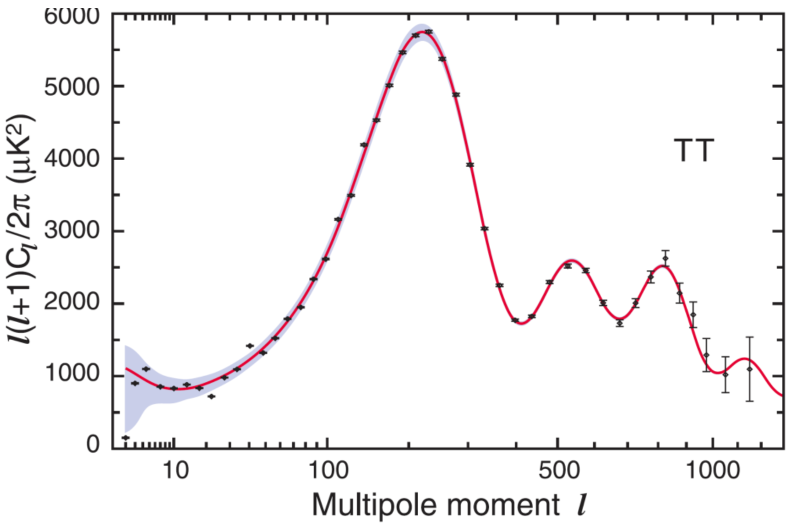
Looking for dark matter off the beaten track

➔ **Find where dark matter *interactions* matter**

<u>Only slightly less well known:</u>

CMB two-point correlation and cross-correlation functions

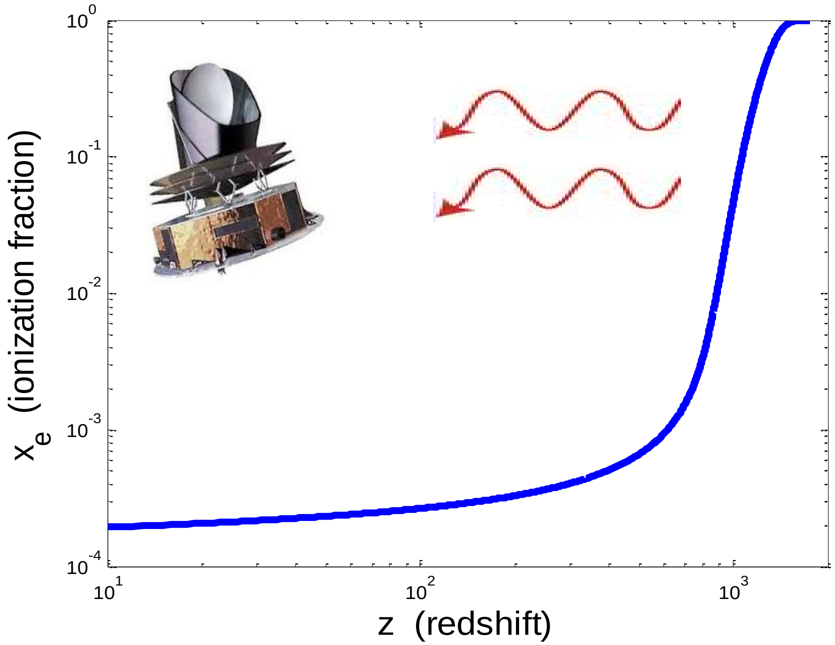




Thomson opacity determines where the photons we see are coming from

$$\dot{\tau}(\eta) = -ac\sigma_T n_e \qquad \tau(\eta) = -\int_{\eta}^{\eta_0} d\eta' \dot{\tau}(\eta')$$

$$g(\eta) = -e^{-\tau(\eta)}\dot{\tau}(\eta)$$



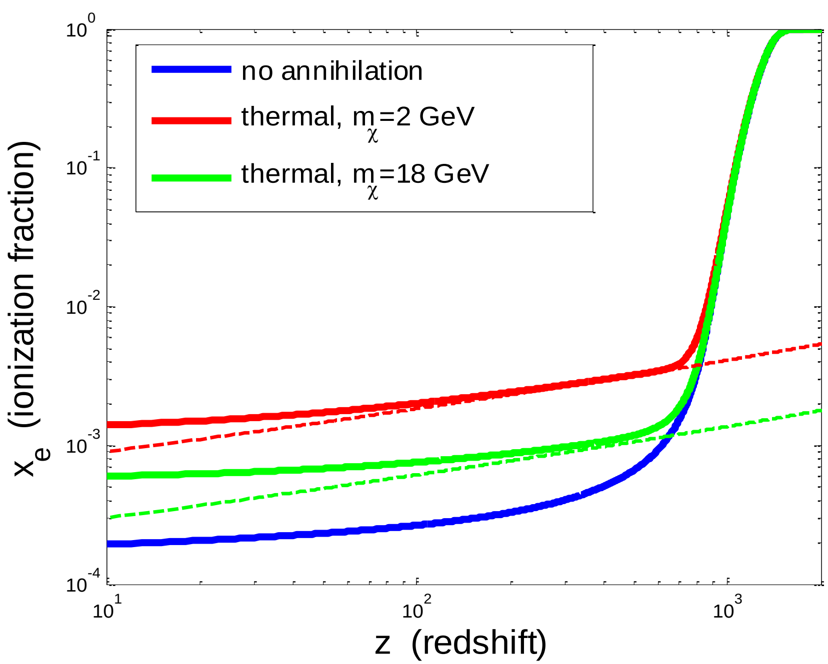
Thomson opacity determines where the photons we see are coming from

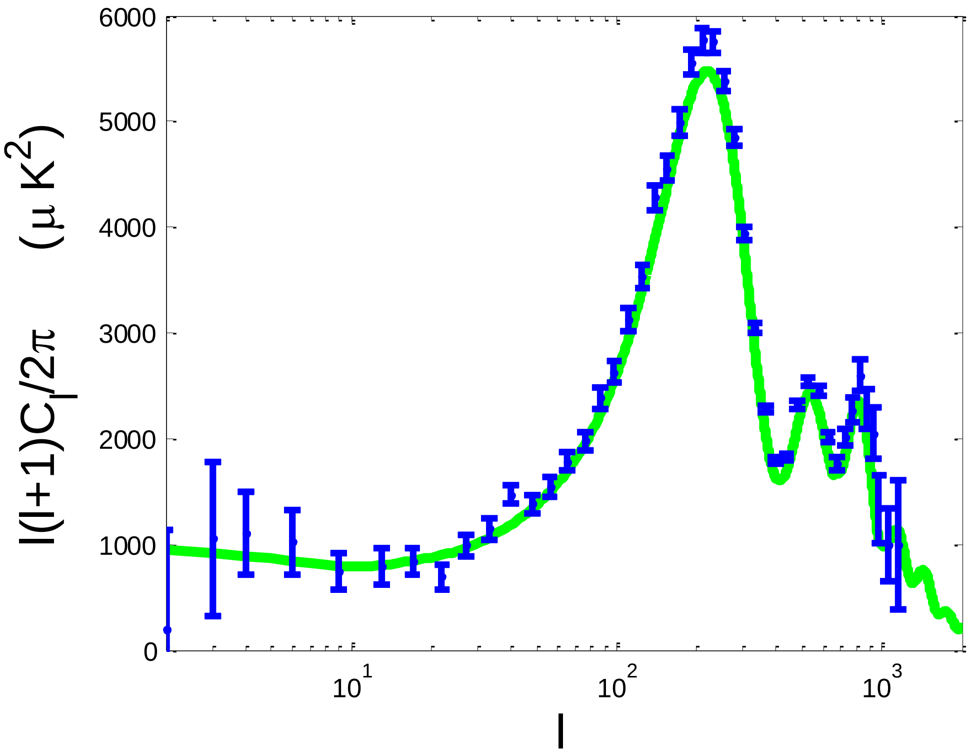
$$\dot{\tau}(\eta) = -ac\sigma_T n_e \qquad\qquad \tau(\eta) = -\int_{\eta}^{\eta_0} d\eta' \dot{\tau}(\eta')$$

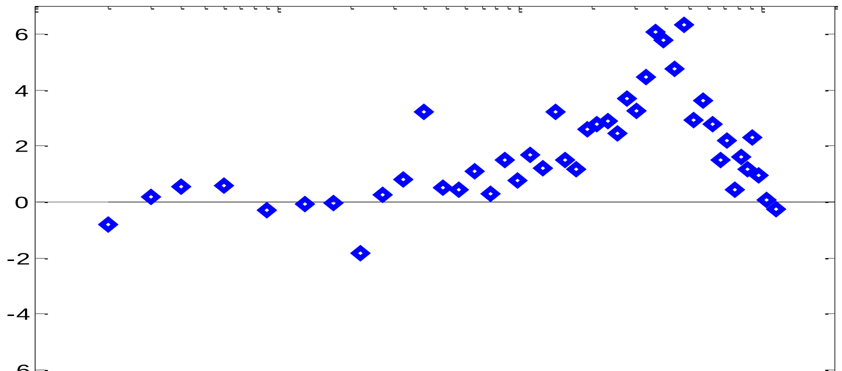
Dark matter annihilation injects energy into the plasma $\dot{u}_{inj}(\vec{x},\eta) = a^4(\eta)\,\frac{\langle\sigma v\rangle}{m_\chi}\rho_\chi^2(\vec{x},\eta)$

Ionizes hydrogen ➔ excess Thomson scattering

$$\Delta T^{\mathrm{obs}}(\hat{n}) \to \Delta T^{\mathrm{rec}}(\hat{n})\, e^{-\Delta\tau}$$

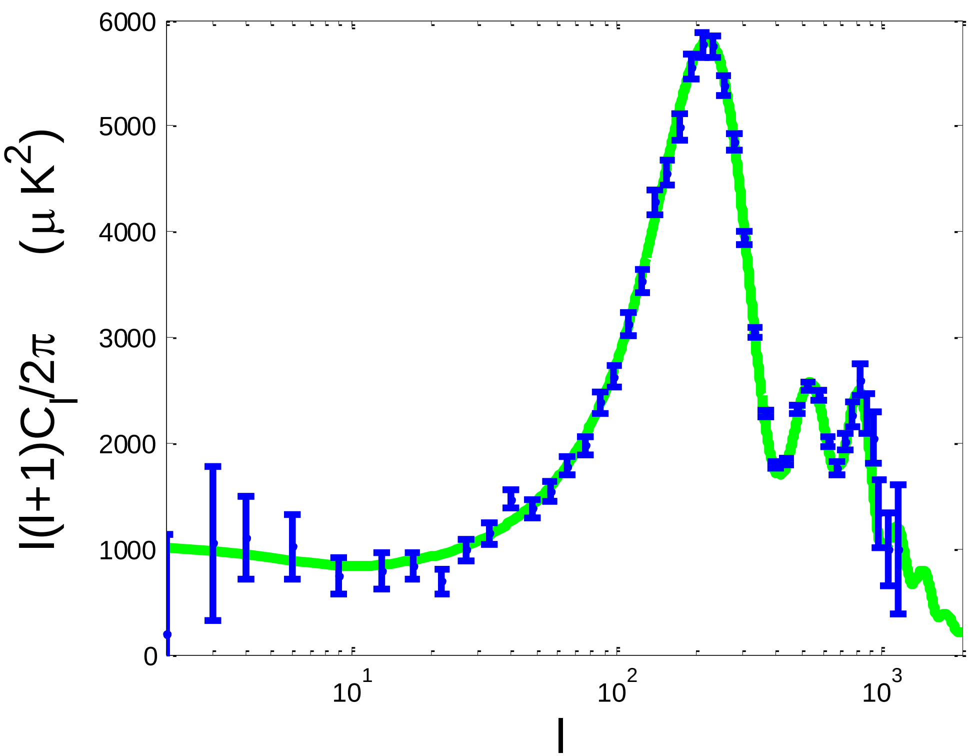


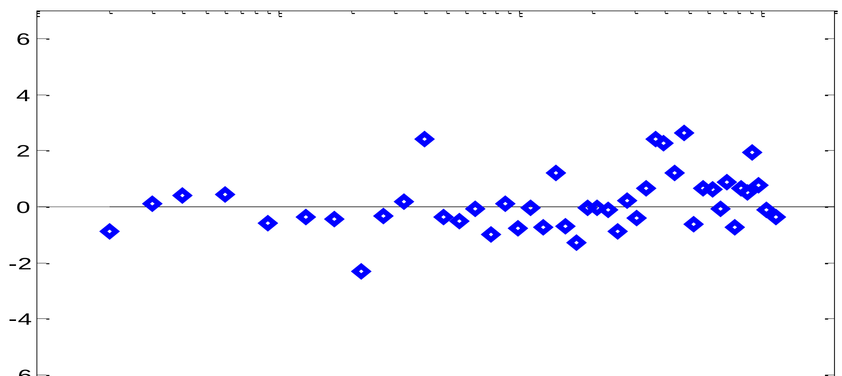




$$x_e^{\rm floor} = \frac{\rho_\chi}{\rho_b}\sqrt{\frac{16}{27}\frac{m_H^2}{m_\chi \epsilon_H}\frac{\langle\sigma v\rangle}{\alpha_H}}$$

How come we can have such large effect?



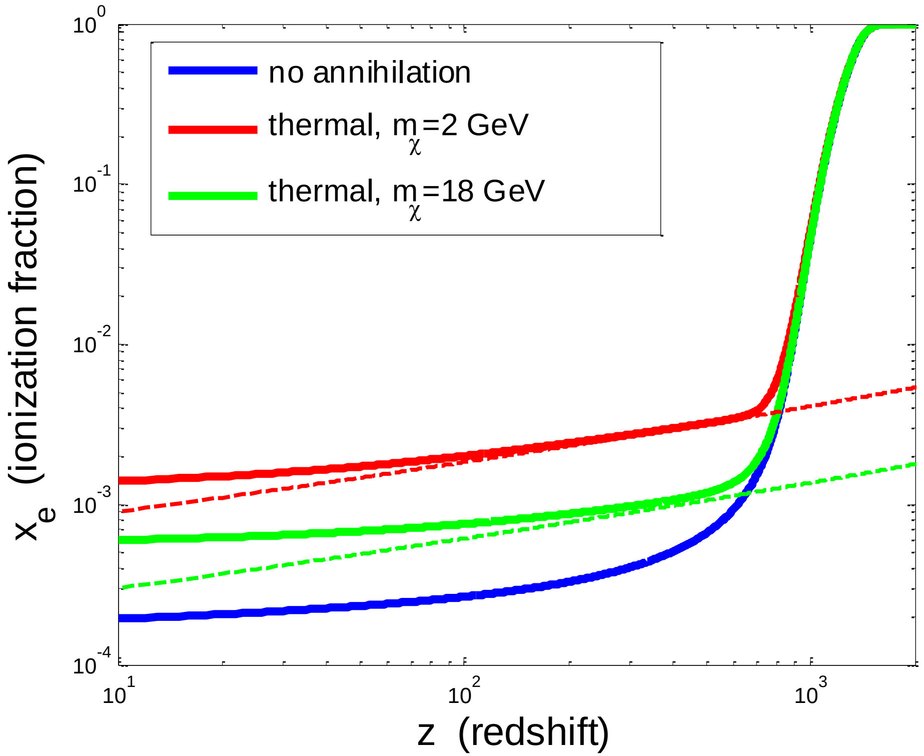


$$x_e^{\text{floor}} = \frac{\rho_\chi}{\rho_b}\sqrt{\frac{16}{27}\frac{m_H^2}{m_\chi \epsilon_H}\frac{\langle \sigma v \rangle}{\alpha_H}}$$

How come we can have such large effect?

Degeneracy.

Padmanabhan & Finkbeiner, PRD72, 023508 (2005)



$$x_e^{\text{floor}} = \frac{\rho_\chi}{\rho_b}\sqrt{\frac{16}{27}\frac{m_H^2}{m_\chi \epsilon_H}\frac{\langle \sigma v \rangle}{\alpha_H}}$$

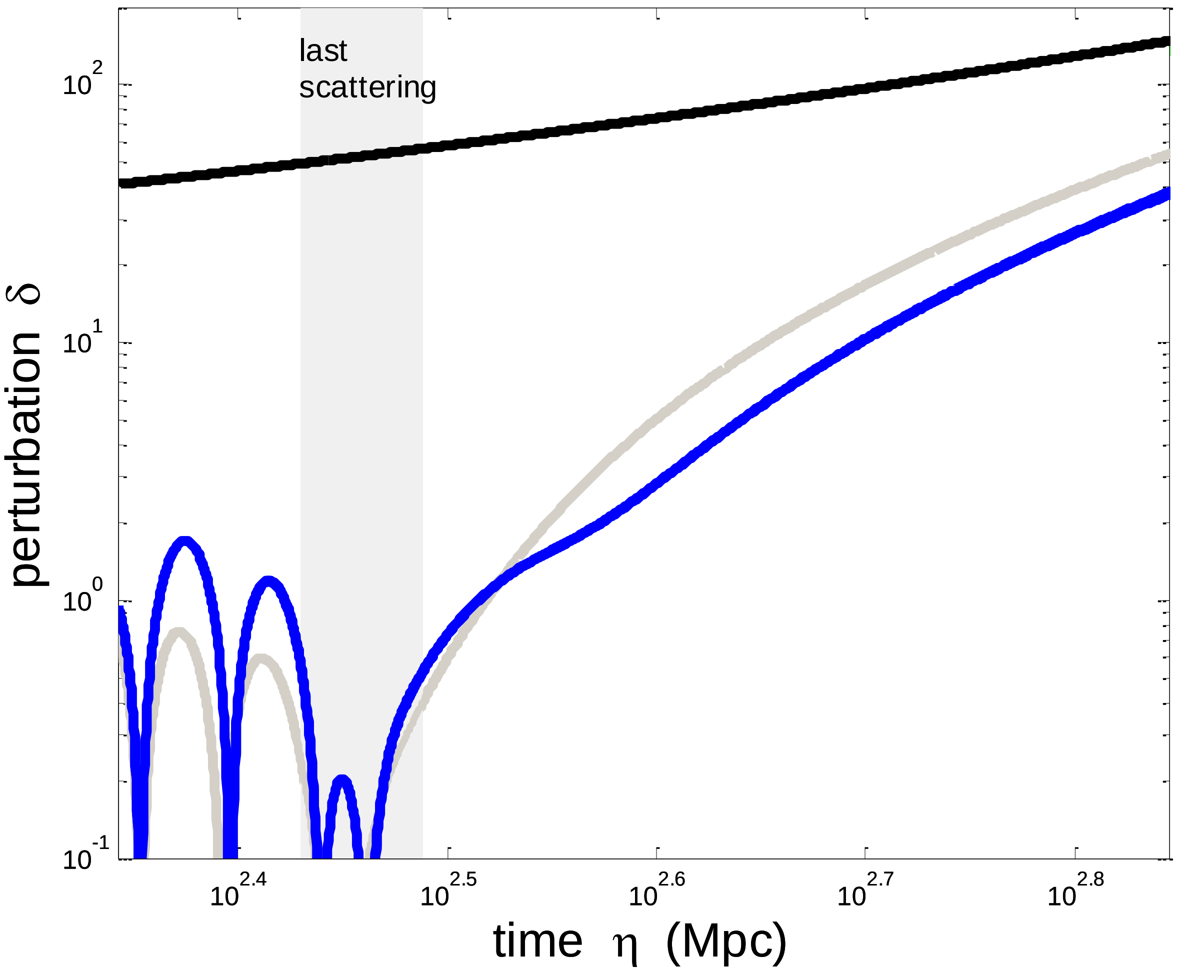
What this means:

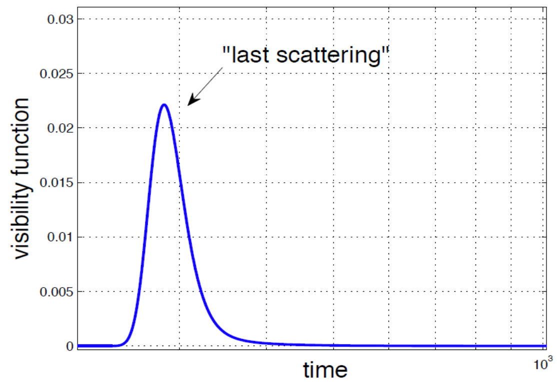
DM annihilation can dominate late recombination

Linear perturbations will try to track DM

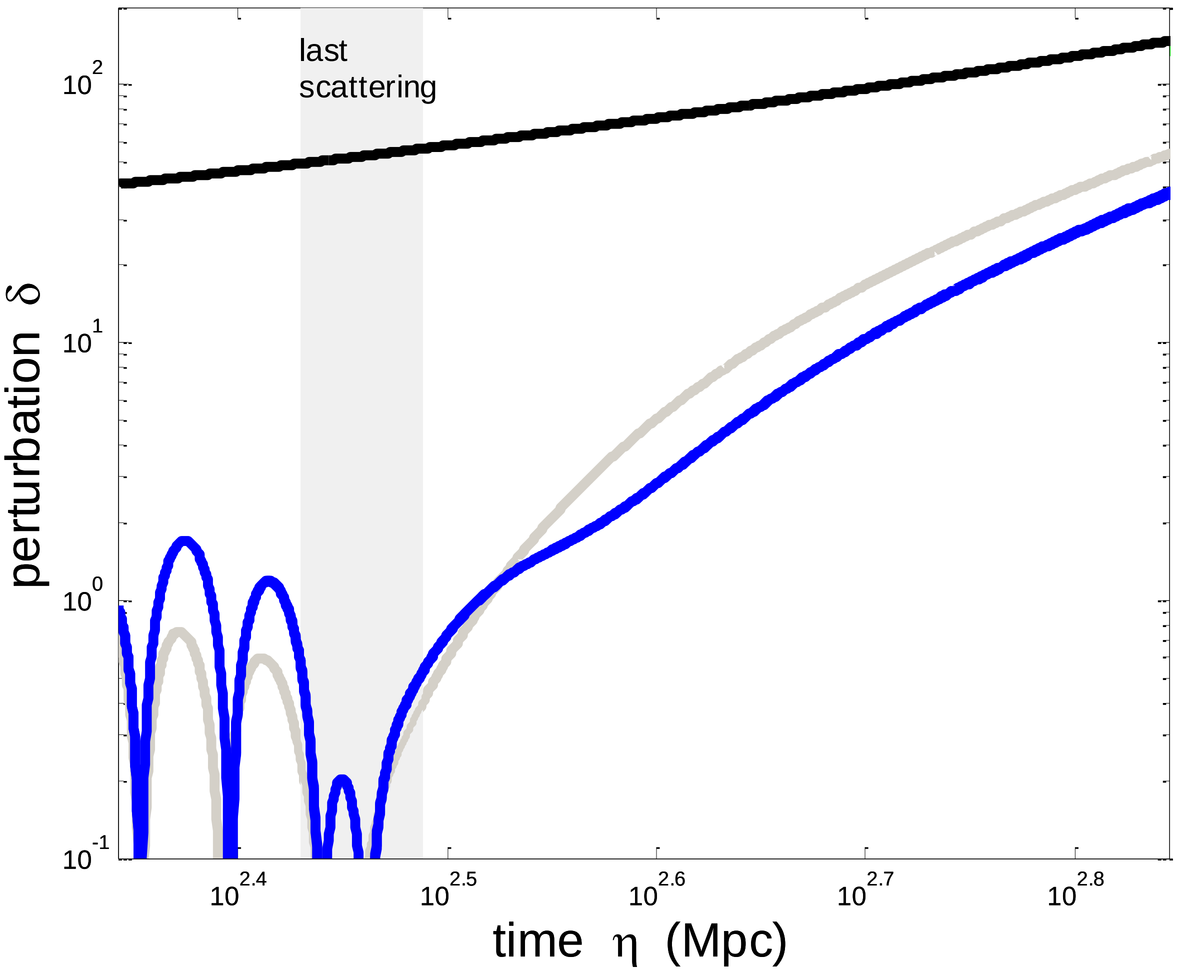
Around the time of recombination,
small scale DM perturbations are orders of magnitude larger than baryons and radiation

➔ baryon/radiation trapped in baryon acoustic oscillations; DM just free falls

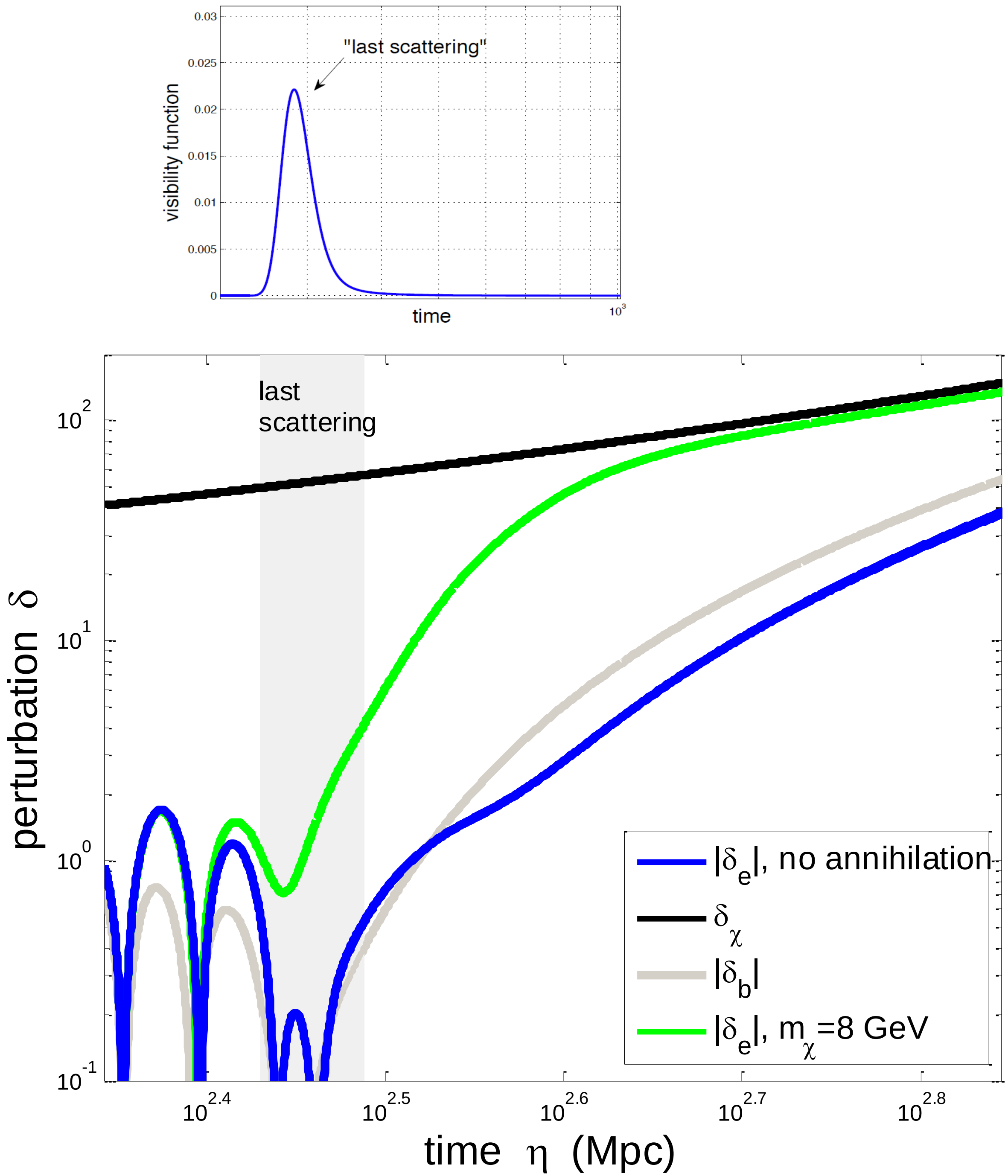




visibility function
"last scattering"
0.03
0.025
0.02
0.015
0.01
0.005
0
time
10^3



last
scattering
perturbation δ
10^2
10^1
10^0
10^{-1}
$10^{2.4}$
$10^{2.5}$
$10^{2.6}$
$10^{2.7}$
$10^{2.8}$
time η (Mpc)



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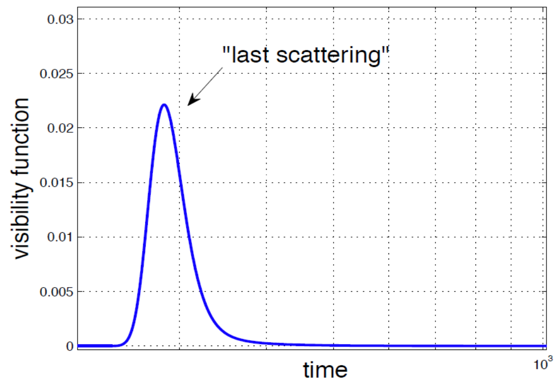
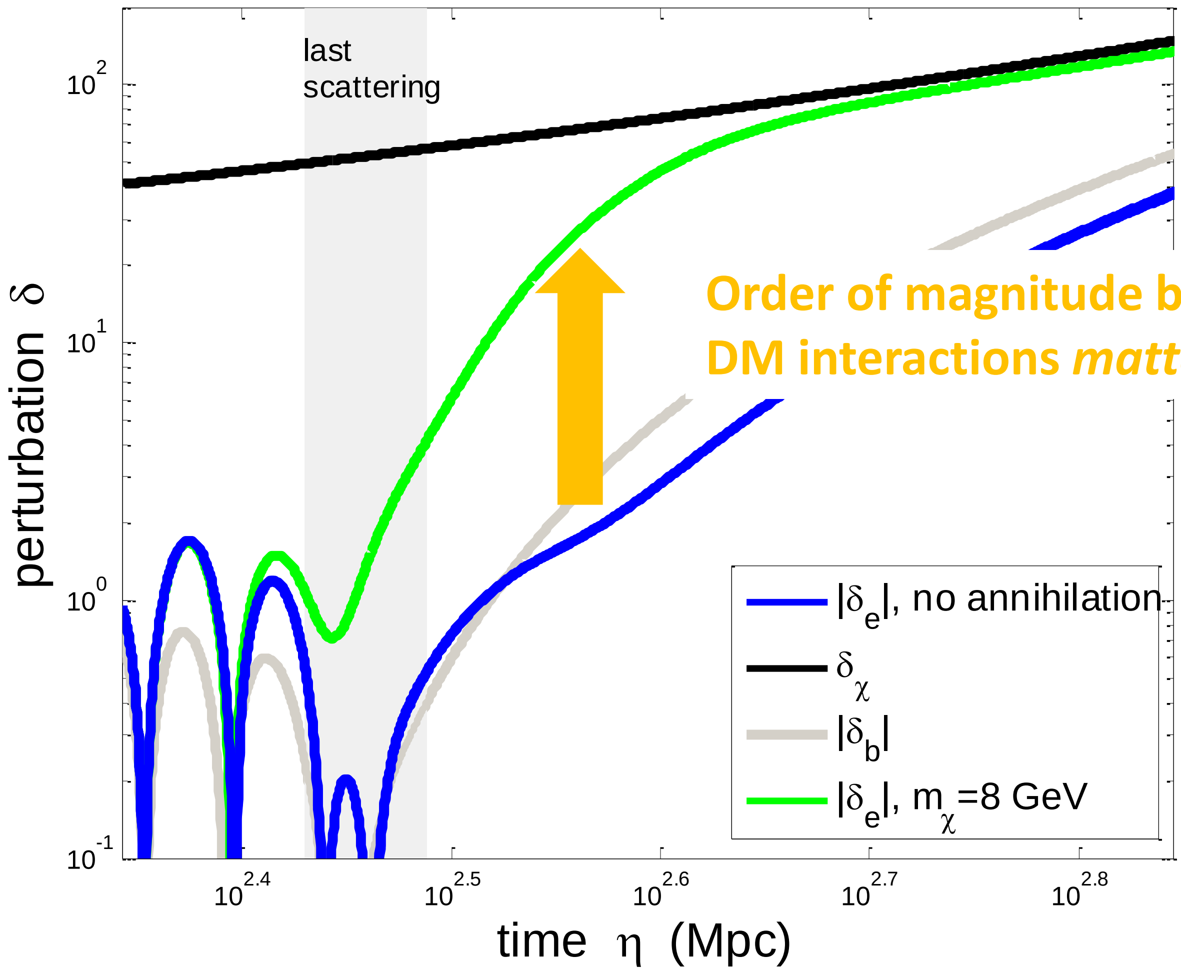
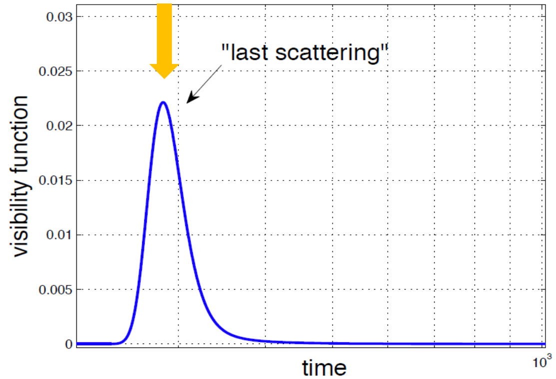
0.01
0.005
0
10^3
last
scattering
perturbation δ
time η (Mpc)
10^2
10^1
10^0
10^{-1}
$10^{2.4}$
$10^{2.5}$
$10^{2.6}$
$10^{2.7}$
$10^{2.8}$
$|\delta_e|$, no annihilation
δ_χ
$|\delta_b|$
$|\delta_e|$, m_χ=8 GeV

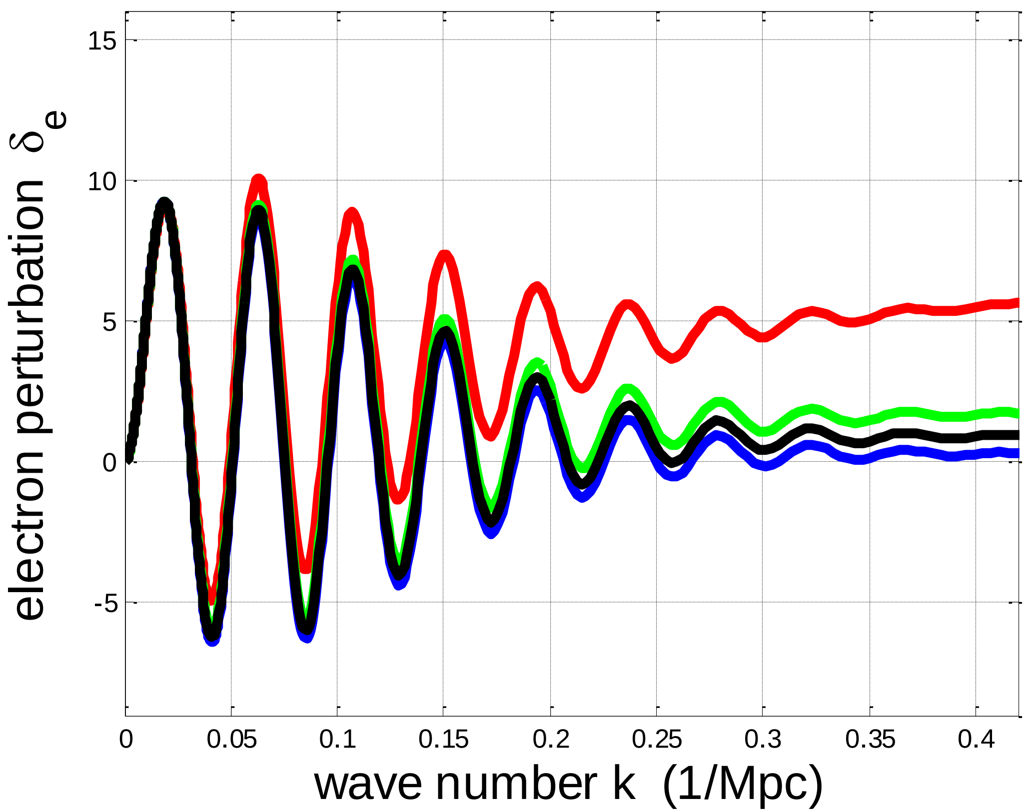


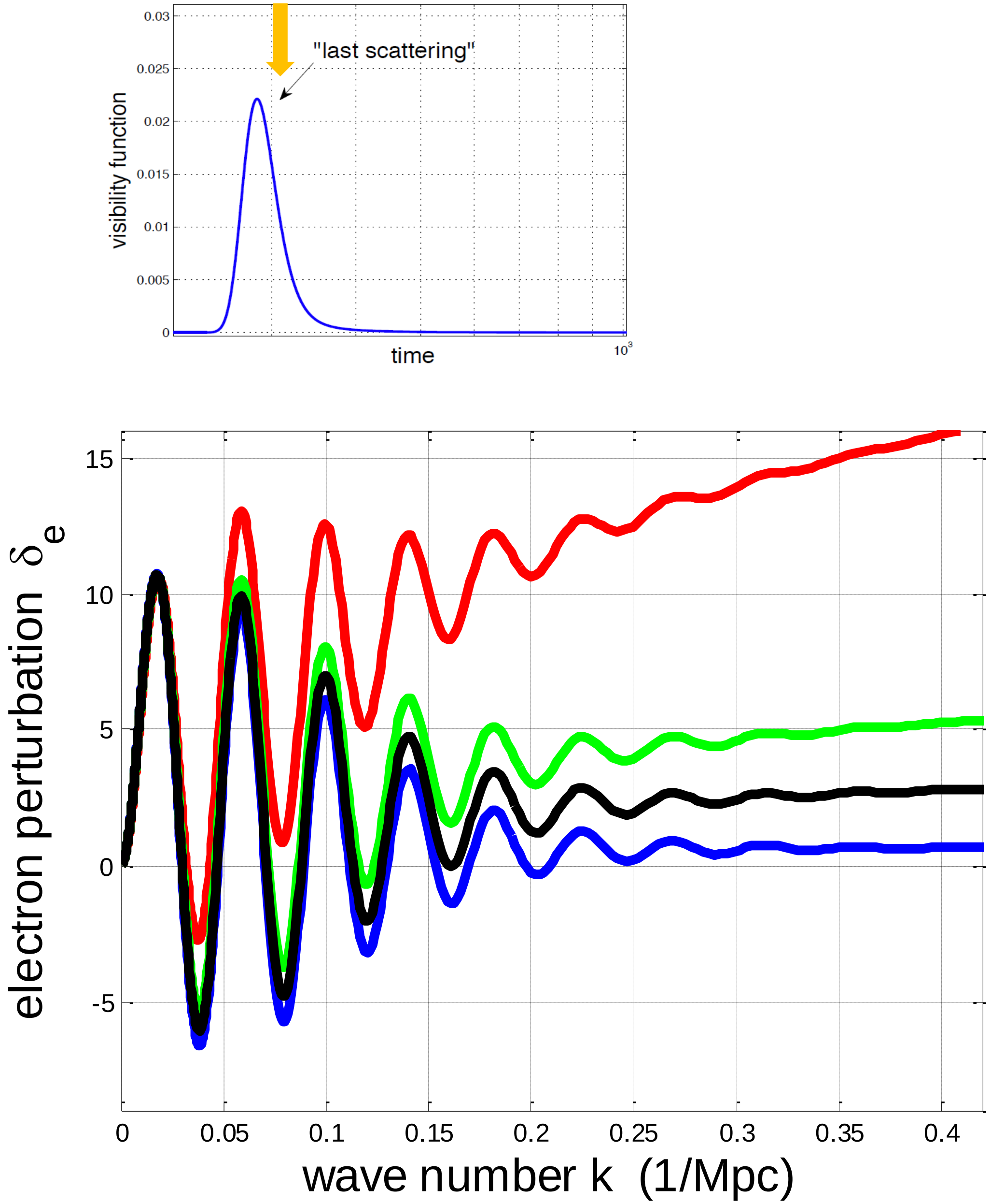


Order of magnitude boost

DM interactions *matter a lot!*


0.03
0.025
0.02
0.015
0.01
0.005
0
visibility function
"last scattering"
time
10^3


15
10
5
0
-5
electron perturbation δ_e
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
wave number k (1/Mpc)



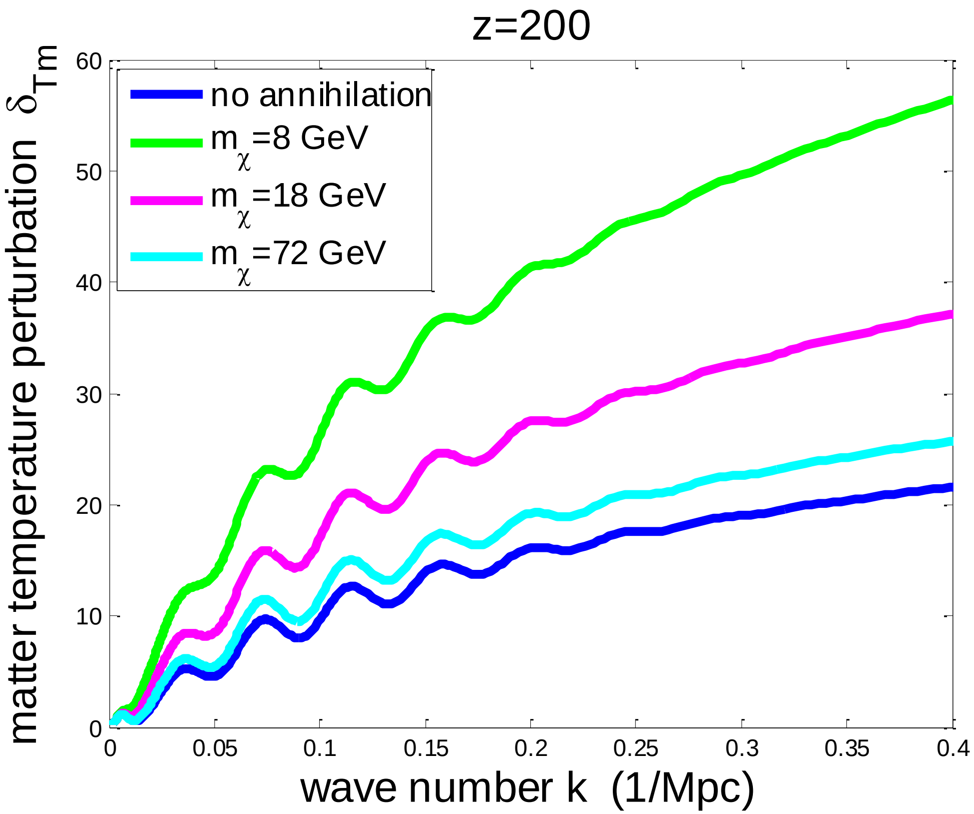
"last scattering"
visibility function
time
electron perturbation δ_e
wave number k (1/Mpc)

During Dark Ages,

Matter temperature more relevant: **21cm**

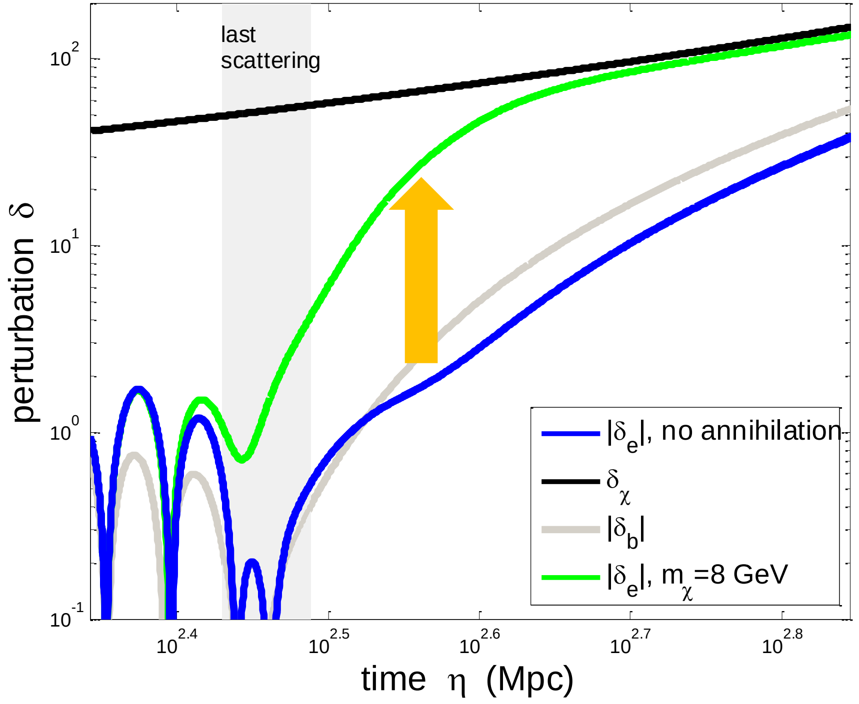
$$\Delta_s \equiv \Delta_{HI} + \frac{\bar{T}_\gamma}{\bar{T}_s - \bar{T}_\gamma}(\Delta_{T_s} - \Delta_{T_\gamma}).$$

e.g. Lewis & Challinor, PRD76, 083005 (2007)



Find where dark matter interactions matter

- cosmological electron density perturbations

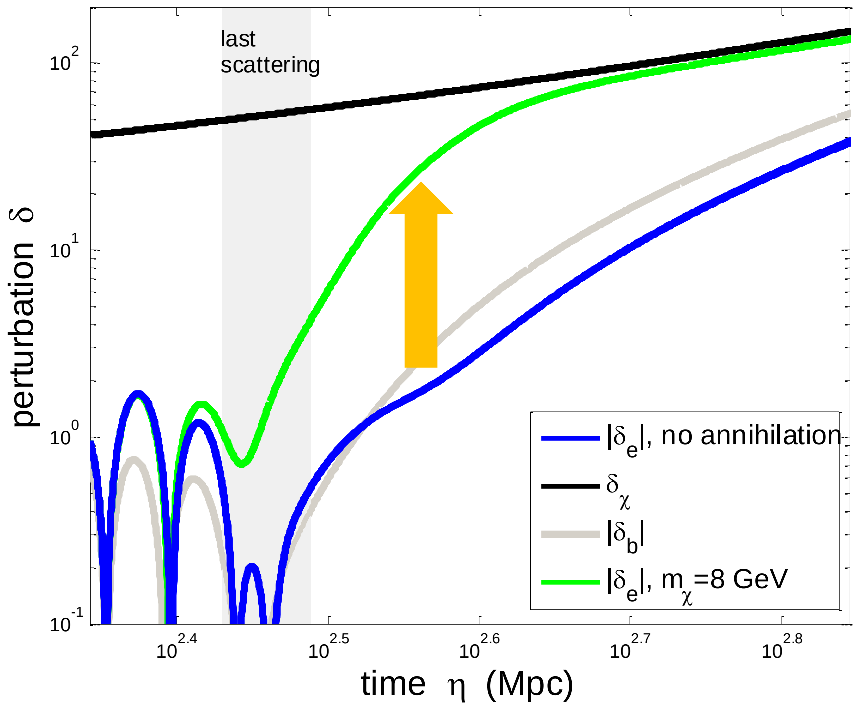


Find where dark matter interactions matter

- cosmological electron density perturbations

Can we detect it

- **CMB non-gaussianity?**
- 21cm



CMB non-gaussianity from recombination

KB, Dvorkin, Zaldarriaga

It's a dangerous business, Frodo, going out of your door. You step into the Road, and if you don't keep your feet, there is no knowing where you might be swept off to.

$$f(\vec{x},\vec{p},\eta) = f_0(\epsilon)\left(1+\Psi(\vec{x},p,\hat{n},\eta)\right)$$

$$F_\gamma(\vec{k},\hat{n},\eta) = \frac{\int d^3q q f_0(q)\Psi}{\int d^3q q f_0(q)}$$

$$\mathcal{G}^{l_1l_2l_3}_{m_1m_2m_3} = \sqrt{\frac{(2\ell_1+1)(2\ell_2+1)(2\ell_3+1)}{4\pi}}\begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ 0 & 0 & 0\end{pmatrix}\begin{pmatrix}\ell_1 & \ell_2 & \ell_3\\ m_1 & m_2 & m_3\end{pmatrix}$$

$$\Psi \to \Psi^{(1)} + \Psi^{(2)}$$

$$\Theta_0 = \frac{1}{16\pi}\int d\hat{n} F_\gamma,$$

$$\Theta_1 = \frac{i}{16\pi}\int d\hat{n}(\hat{k}\cdot\hat{n})F_\gamma,$$

$$\Theta_2 = -\frac{3}{32\pi}\int d\hat{n}\left((\hat{k}\cdot\hat{n})^2-\frac{1}{3}\right)F_\gamma$$

$$\Theta^{(1)}(\vec{k},\eta,\hat{n}) = \sum_l (-i)^l(2l+1)\mathcal{P}_l(\mu_k)\Theta^{(1)}_l(\vec{k},\eta)$$

$$\mu_k = \hat{k}\cdot\hat{n}$$

$$B^{\ell_1\ell_2\ell_3}_{m_1m_2m_3} = \mathcal{G}^{l_1l_2l_3}_{m_1m_2m_3} \times \frac{4}{\pi^2}\int_0^{\eta_0} d\eta g(\eta)\left(f_{\ell_1}(\eta)g_{\ell_2}(\eta) + \text{five permutations}\right),$$

$$g_\ell(\eta) = \int dk k^2 P(k)\Theta^{(1)}_\ell(k,\eta_0)\, j_\ell[k(\eta_0-\eta)]\delta_e(k,\eta),$$

$$f_\ell(\eta) = (-1)^l\int dk k^2 P(k)\Theta^{(1)}_\ell(k,\eta_0)\sum_{l',l''}(2l'+1)(2l''+1)\begin{pmatrix}\ell & \ell' & \ell''\\ & & \end{pmatrix}^2 i^{l+l'+l''} j_{l'}[k(\eta_0-\eta)]$$

$$\times\left(\delta_{l''1}\frac{\theta_b^{(1)}(k,\eta)-\theta_\gamma^{(1)}(k,\eta)}{3k} + \delta_{l''2}\frac{\Pi^{(1)}(k,\eta)}{10} - (1-\delta_{l''0})(1-\delta_{l''1})\Theta^{(1)}_{l''}(k,\eta)\right).$$

$$\ddot{\Theta}_0 + k^2c_s^2\left(1 - R\partial_\eta\left[\frac{R}{\dot{\tau}(1+R)}\right]\right)\Theta_0 - \frac{k^2c_s^2}{\dot{\tau}}\left(\frac{16}{15}+\frac{R^2}{1+R}\right)\dot{\Theta}_0 + F = S_{k_D} + S_{c_s} + S_F$$

$$S_{k_D} = -\frac{k^2c_s^2}{\dot{\tau}}\int\frac{d^3q}{(2\pi)^3}\left(\frac{16}{15}\mathcal{P}_2\left(\hat{k}\cdot\hat{q}\right) + \frac{R^2}{1+R}\frac{q}{k}\mathcal{P}_1\left(\hat{k}\cdot\hat{q}\right)\right)\delta_e(\vec{k}-\vec{q})\,\dot{\Theta}^{(1)}_0(\vec{q})$$

$$c_s^2 = \frac{1}{3(1+R)}, \quad F = \frac{\ddot{h}}{6} + \frac{15k^2c_s^2\dot{\kappa}}{16\dot{\tau}}$$

$$S_{c_s} = -k^2c_s^2\int\frac{d^3q}{(2\pi)^3}\frac{q}{k}\mathcal{P}_1\left(\hat{k}\cdot\hat{q}\right)R\partial_\eta\left(\frac{R}{\dot{\tau}(1+R)}\delta_e(\vec{k}-\vec{q})\right)\Theta^{(1)}_0(\vec{q})$$

$$S_F = \frac{k^2c_s^2}{\dot{\tau}}\int\frac{d^3q}{(2\pi)^3}\frac{16}{15}\mathcal{P}_2\left(\hat{k}\cdot\hat{q}\right)\delta_e(\vec{k}-\vec{q})\,\dot{\kappa}^{(1)}(\vec{q})$$

$$\eta\dot{\tau},\quad (\dot{\tau}/k) \gg 1$$

CMB non-gaussianity

$$B^{\ell_1 \ell_2 \ell_3}_{m_1 m_2 m_3} = \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$$

Probe of inflation

Maldacena, JHEP 0305 (2003) 013
Acquaviva et al, Nuclear Physics B 667 (2003) 119

CMB non-gaussianity

$$B^{\ell_1\ell_2\ell_3}_{m_1m_2m_3} = \langle a_{\ell_1m_1}a_{\ell_2m_2}a_{\ell_3m_3}\rangle$$

WMAP9 (Benett et al, arxiv:1212.5225)

$$\begin{aligned}
f_{NL}^{\rm loc} &= 37.2 \pm 19.9 \qquad && (-3 < f_{NL}^{\rm loc} < 77 \text{ at } 95\% \text{ CL}) \\
f_{NL}^{\rm eq} &= 51 \pm 136 \qquad && (-221 < f_{NL}^{\rm eq} < 323 \text{ at } 95\% \text{ CL}) \\
f_{NL}^{\rm orth} &= -245 \pm 100 \qquad && (-445 < f_{NL}^{\rm orth} < -45 \text{ at } 95\% \text{ CL})
\end{aligned}$$

CMB non-gaussianity

$$B^{\ell_1 \ell_2 \ell_3}_{m_1 m_2 m_3} = \langle a_{\ell_1 m_1} a_{\ell_2 m_2} a_{\ell_3 m_3} \rangle$$

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$$f_{NL}^{\rm orth} = -245 \pm 100 \qquad (-445 < f_{NL}^{\rm orth} < -45 \text{ at } 95\% \text{ CL})$$

Should vanish for single-field inflation

Creminelli & Zaldarriaga, M.2004, JCAP, 0410, 006

CMB non-gaussianity from recombination

$$B^{\ell_1\ell_2\ell_3}_{m_1m_2m_3} = \langle a_{\ell_1m_1}a_{\ell_2m_2}a_{\ell_3m_3}\rangle$$

WMAP9 (Benett et al, arxiv:1212.5225)

$$\begin{aligned} f_{NL}^{\rm loc} &= 37.2 \pm 19.9 \qquad && (-3 < f_{NL}^{\rm loc} < 77 \text{ at } 95\% \text{ CL}) \\ f_{NL}^{\rm eq} &= 51 \pm 136 \qquad && (-221 < f_{NL}^{\rm eq} < 323 \text{ at } 95\% \text{ CL}) \\ f_{NL}^{\rm orth} &= -245 \pm 100 \qquad && (-445 < f_{NL}^{\rm orth} < -45 \text{ at } 95\% \text{ CL}) \end{aligned}$$

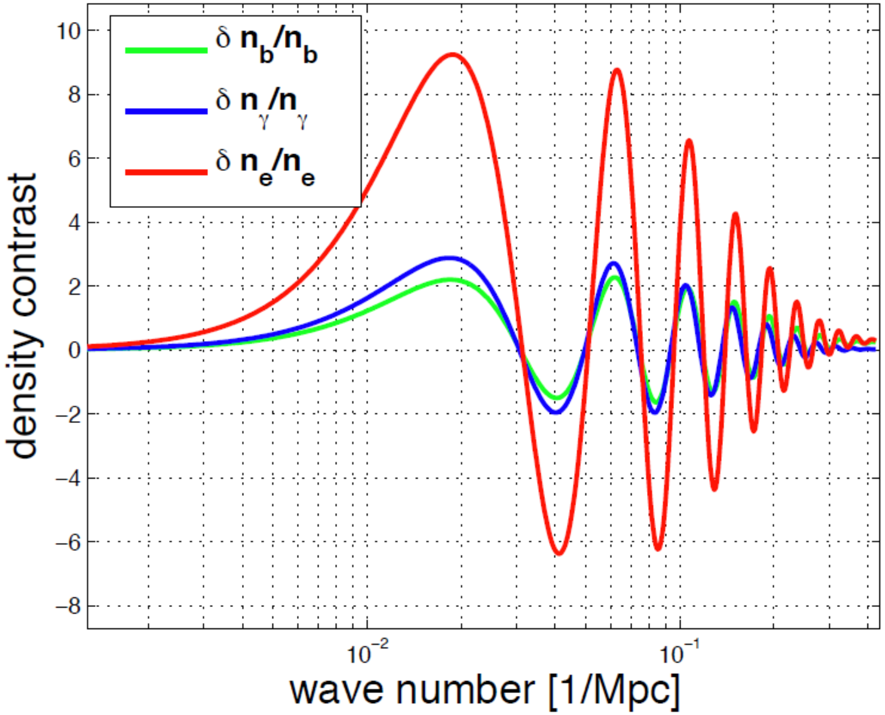
Well in the ballpark of the effects we discuss here.
Need to compute the Standard Model prediction

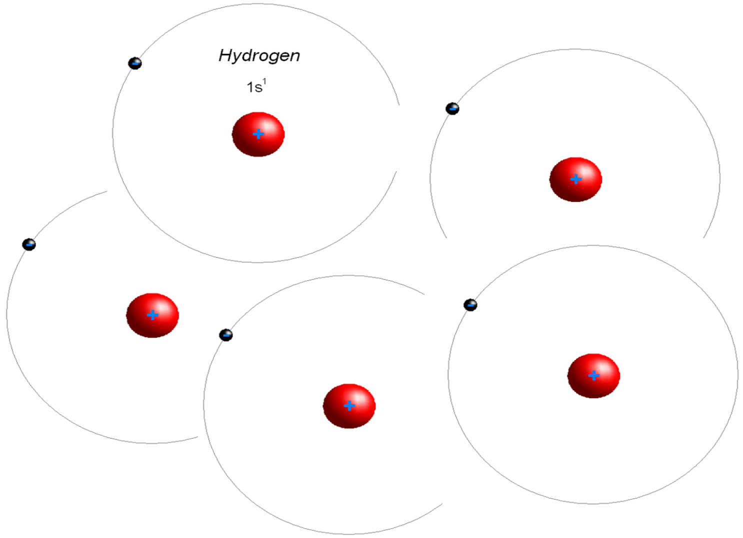
2$^{\rm nd}$ order perturbation theory – better pick dominant terms

CMB non-gaussianity from recombination

Why electron perturbations matter

Ionization "wild card"

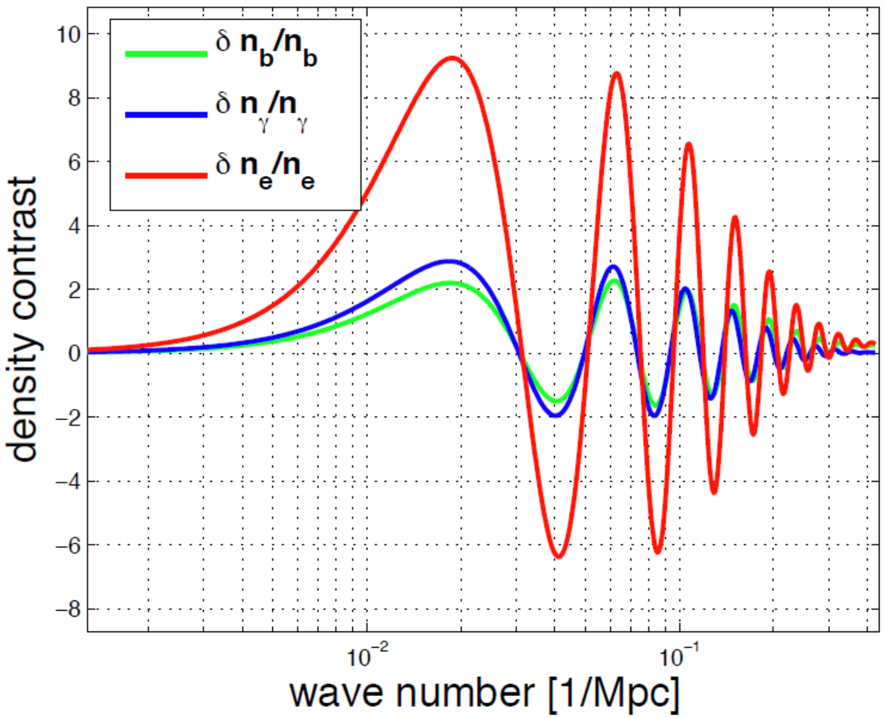


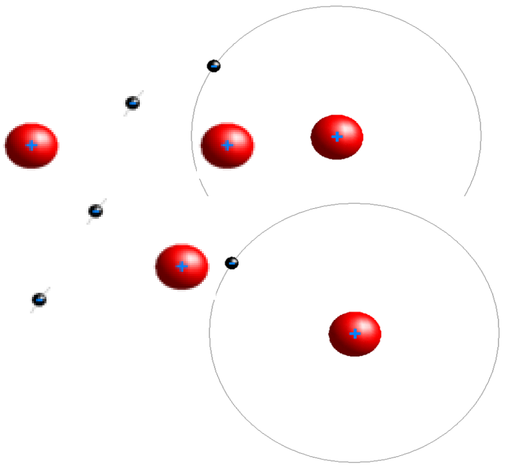


CMB non-gaussianity from recombination

Why electron perturbations matter

Ionization “wild card”



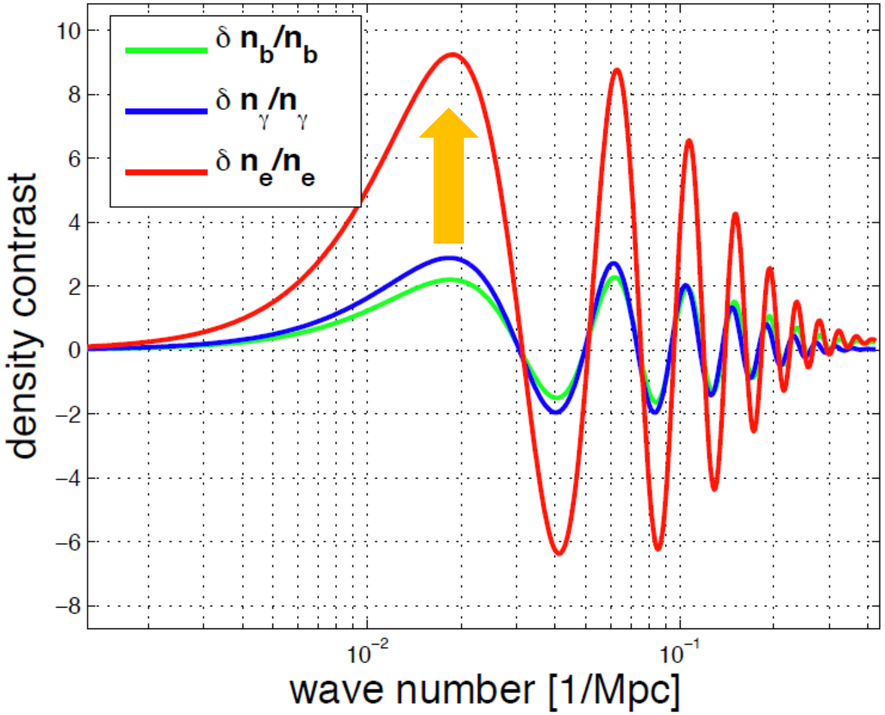


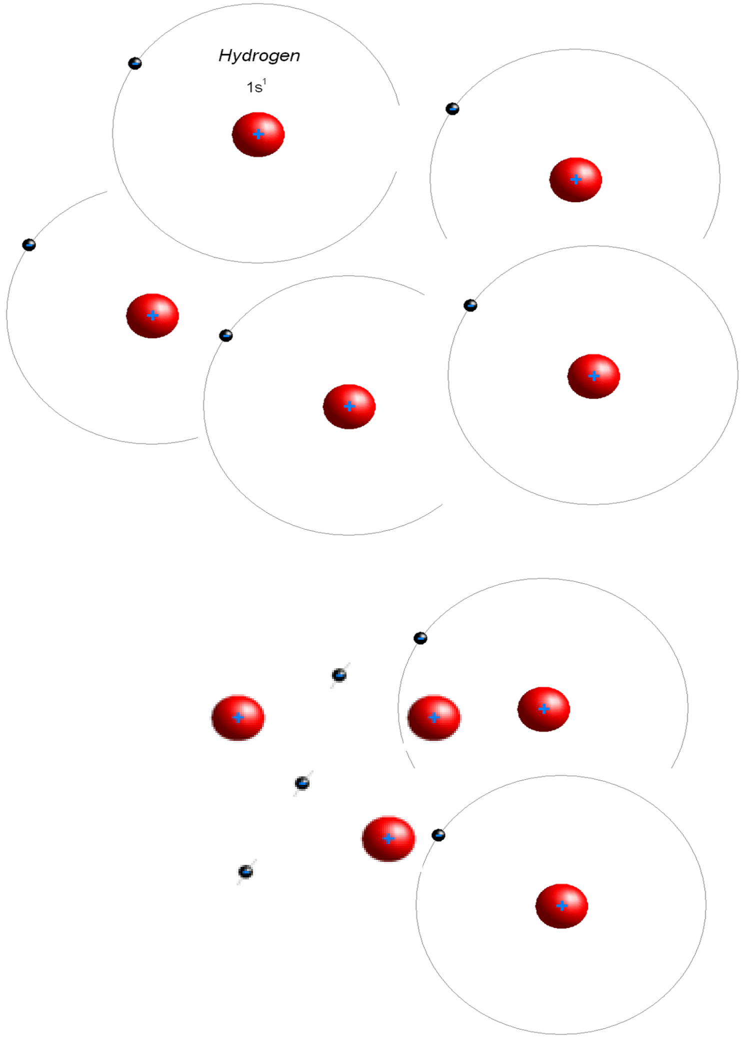
CMB non-gaussianity from recombination

Why electron perturbations matter

Ionization "wild card"

Electron pert' ~ 5 x baryon pert'





CMB non-gaussianity from recombination

1. Second order feedback

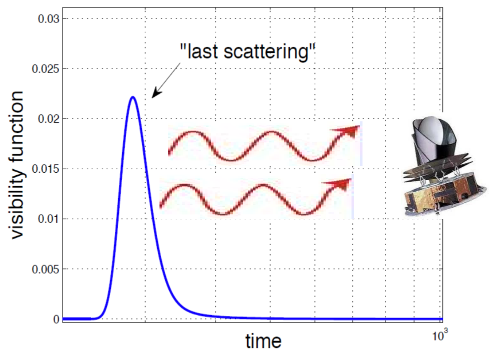
electron perturbation induce temperature multipoles at second order
analytical calculation ***lacking***.

2. Perturbed visibility

un-isotropic optical depth for Thomson scattering

$$\Delta T^{\rm obs}(\hat{n}) \rightarrow \Delta T^{\rm rec}(\hat{n})\, e^{-\Delta\tau(\hat{n})}$$

$$\langle \Delta T^{\rm obs} \Delta T^{\rm obs} \Delta T^{\rm obs} \rangle \rightarrow -\langle \Delta T^{\rm rec} \Delta T^{\rm rec} \Delta T^{\rm rec} \Delta\tau \rangle$$



done: Senatore, Tassev, Zaldarriaga, JCAP 0908, 031 (2009)
Khatri & Wandelt, PRD79, 023501 (2009)

CMB non-gaussianity from recombination

Second order feedback: simple *just before* recombination

…one famous **Harmonic Oscillator**

$$\ddot{X} + \omega^2 X + iq\omega \dot{X} + F = 0$$

CMB non-gaussianity from recombination

Second order feedback: simple *just before* recombination

…one famous **Harmonic Oscillator**

Temperature monopole Θ_0

$$\ddot{\Theta}_0 + \overbrace{k^2 c_s^2 \left(1 - R\partial_\eta \left[\frac{R}{\dot{\tau}(1+R)}\right]\right)}^{\omega^2} \Theta_0 - \overbrace{\frac{k^2 c_s^2}{\dot{\tau}} \left(\frac{16}{15} + \frac{R^2}{1+R}\right)}^{iq\omega} \dot{\Theta}_0 + F =$$

CMB non-gaussianity from recombination

Second order feedback: simple *just before* recombination

…one famous **Harmonic Oscillator**

Temperature monopole Θ_0

$$\ddot{\Theta}_0 + \overbrace{k^2 c_s^2 \left(1 - R\partial_\eta\left[\frac{R}{\dot{\tau}(1+R)}\right]\right)}^{\omega^2}\Theta_0 - \overbrace{\frac{k^2 c_s^2}{\dot{\tau}}\left(\frac{16}{15} + \frac{R^2}{1+R}\right)}^{iq\omega}\dot{\Theta}_0 + F = S_{k_D}$$

Silk damping perturbed

$$S_{k_D} = -\frac{k^2 c_s^2}{\dot{\tau}}\int \frac{d^3q}{(2\pi)^3}\left(\frac{16}{15}\mathcal{P}_2\left(\hat{k}\cdot\hat{q}\right) + \frac{R^2}{1+R}\frac{q}{k}\mathcal{P}_1\left(\hat{k}\cdot\hat{q}\right)\right)\delta_e(\vec{k}-\vec{q})\,\dot{\Theta}_0^{(1)}(\vec{q})$$

CMB non-gaussianity from recombination

Second order feedback: simple *just before* recombination

...one famous **Harmonic Oscillator**

Temperature monopole Θ_0

$$\ddot{\Theta}_0 + \underbrace{k^2 c_s^2 \left(1 - R\partial_\eta\left[\frac{R}{\dot{\tau}(1+R)}\right]\right)}_{\omega^2}\Theta_0 - \underbrace{\frac{k^2 c_s^2}{\dot{\tau}}\left(\frac{16}{15} + \frac{R^2}{1+R}\right)}_{iq\omega}\dot{\Theta}_0 + F = S_{k_D} + S_{c_s}$$

Sound speed perturbed

$$S_{c_s} = -k^2 c_s^2 \int \frac{d^3q}{(2\pi)^3}\frac{q}{k}\mathcal{P}_1\left(\hat{k}\cdot\hat{q}\right) R\partial_\eta\left(\frac{R}{\dot{\tau}(1+R)}\delta_e(\vec{k}-\vec{q})\right)\Theta_0^{(1)}(\vec{q})$$

CMB non-gaussianity from recombination

Second order feedback: simple *just before* recombination

…one famous **Harmonic Oscillator**

Temperature monopole Θ_0

$$\boxed{\ddot{\Theta}_0 + \overbrace{k^2 c_s^2 \left(1 - R\partial_\eta \left[\frac{R}{\dot{\tau}(1+R)}\right]\right)}^{\omega^2} \Theta_0 - \overbrace{\frac{k^2 c_s^2}{\dot{\tau}} \left(\frac{16}{15} + \frac{R^2}{1+R}\right)}^{iq\omega} \dot{\Theta}_0 + F = S_{k_D} + S_{c_s} + S_F}$$

Baryon drag perturbed

$$S_F = \frac{k^2 c_s^2}{\dot{\tau}} \int \frac{d^3 q}{(2\pi)^3} \frac{16}{15} \mathcal{P}_2 \left(\hat{k} \cdot \hat{q}\right) \delta_e(\vec{k} - \vec{q})\, \dot{\kappa}^{(1)}(\vec{q})$$

CMB non-gaussianity from recombination

Second order feedback: simple *just before* recombination

- Compute analytically in tight coupling approximation
- Identify relevant processes explicitly: Silk damping; sound speed; baryon drag

Little chance to see dark matter effect in bispectrum… cumulative accidents

1. Rise time too slow: boost maximal after peak visibility
2. Too small scale: cannot inject power efficiently from short wave electron perturbation down to long wave photon multipole
3. Too small scale: cannot affect diffusion damping by electron perturbation on scale smaller than diffusion mean free path

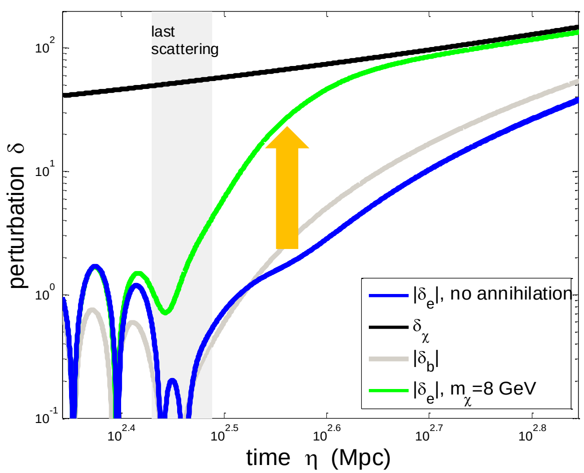
Beauty of it is: found unsolved problem and solved it. Will eventually be measured!

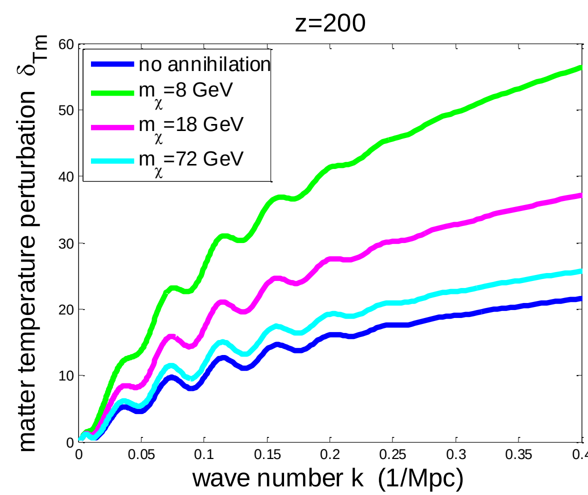
Summary

- Hunt for WIMPs and their like: $\Omega_{dm} \sim 5\ \Omega_b$

- Find where dark matter interactions matter

Perturbations to free electron density: order of magnitude amplification
Perturbations to kinetic matter temperature, into dark ages: 21cm?



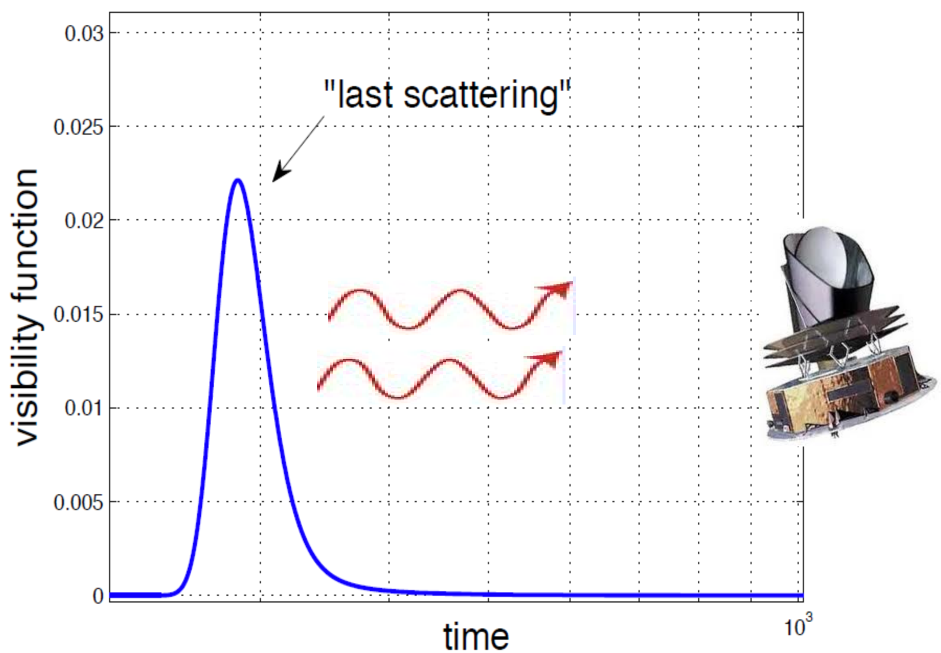


Continue to look off the beaten track – next time we get it

- Recombination bispectrum: found an unsolved problem and solved it

Thank you!

Xtra



"last scattering"
visibility function
time
0.03
0.025
0.02
0.015
0.01
0.005
0
10^3

Guiding concept: The solar neutrino problem

• Consider a major success of particle astrophysics: Solar Neutrinos

Case was only closed when astro uncertainties were removed model independently. Done from basic principles, combining different data

- Low energy deficit (Homestake) – could attribute to T uncertainty

- Smaller deficit at higher energy (Kamiokande) ➔ *real* anomaly

• **Lesson**:

model independent

no-go conditions